THE ACQUISITION OF

FLAT PANEL DISPLAYS

FOR

MILITARY APPLICATIONS

March 1998

Office of the Under Secretary of Defense

for Acquisition and Technology

PREFACE

This report was prepared for the Office of the Under Secretary of Defense for Acquisition and Technology in response to a Congressional request for a study of the acquisition of flat panel displays for military applications. This work was performed under the auspices of a Department of Defense Steering Group by the following team:

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EXECUTIVE SUMMARY

The Senate Armed Services Committee requested the Under Secretary of Defense for Acquisition and Technology to conduct a study of flat panel display (FPD) acquisition for military applications. The Committee's tasking to the Department of Defense (DoD) called for an assessment of how DoD program managers and contractors have made tradeoffs in acquiring "consumer-grade displays" rather than acquiring "FPD systems that are custom designed to meet military requirements." The Committee requested that the following aspects of FPD acquisition be addressed:

- "life cycle cost and performance tradeoffs"
- "environmental and performance requirements and test data on performance of both custom and consumer-grade FPD"
- "life cycle cost and support issues such as commonality, supportability, and availability"
- "potential benefits of FPD system interface standards and open systems approaches"

FPDs are a specific example of the insertion of emerging dual-use technology into defense systems. This insertion has been affected by the changes in practices brought about by DoD's Acquisition Reform Initiative. This study provides some insights into the broader implementation of commercial technology insertion within DoD.

The primary findings, conclusions, and recommendations concerning these issues are as follows:

COST AND PERFORMANCE TRADEOFFS

Few programs or contractors explicitly performed tradeoffs of life cycle cost (LCC) and performance in the acquisition of FPD systems.

In initial military FPD development programs, domestic custom producers had major problems delivering FPDs that met performance specifications. In order to stay on schedule, several display integrators and prime contractors using custom FPDs spent additional development funds, and DoD program managers relaxed initial performance specifications. Certain programs sought alternative sources while others determined that lesser capabilities were acceptable to meet the user's needs and allowed the use of ruggedized consumer-grade FPDs. Generally LCC was not a primary factor in making these tradeoff decisions. FPDs are an emerging technology for which there are little data available on long-term performance, cost, and availability. In addition there have been heavy pressures placed on integrators to reduce up-front procurement costs and meet delivery schedules.

DoD's acquisition reform measures appear to be effective in providing programs with the flexibility to meet their needs using available commercial technology. However, given the lack of attention to LCC, questions have been raised whether "best value" contracting has been reduced simply to lowest initial acquisition cost. This study's findings on test data and LCC indicate that this is a valid concern.

REQUIREMENTS AND TEST DATA

Appropriately ruggedized consumer-grade FPDs can meet the environmental and performance requirements for a broad range of military applications, including shipboard, command and control, army ground vehicles, military transport aviation, and soldier-portable computer systems. Currently, ruggedized consumer-grade FPDs cannot meet the specifications for some highly stressful applications, particularly tactical cockpit avionics.

Due to lack of comparable and available data, programs have reached different judgments about the environmental tolerance and optical performance of ruggedized consumer-grade FPDs. There appear to be few systematic assessments of display performance impact on mission effectiveness.

FPDs are rapidly entering the DoD weapons inventory across a wide range of applications. FPDs are qualified by individual vendors against contracted environmental and performance requirements. Thus, there are extensive test data on selected consumer-grade and custom FPDs. However, these data are mostly program specific, not sufficient for conducting comparative analyses of consumer-grade displays and custom displays, and generally not shared.

LCC AND SUPPORT ISSUES

Few formal evaluations tied specific FPD system performance characteristics to LCC. Furthermore, the LCC of a proposed FPD system was rarely used as a primary selection criterion.

Both consumer-grade and custom FPDs provide significant LCC benefits to military programs. The cost of qualifying new displays to cope with rapid commercial product obsolescence could make the LCC associated with consumer-grade FPDs greater than that of custom FPDs. However, custom FPDs can have higher LCC due to higher development and procurement costs as well as their own obsolescence risks. Commonality across programs using a design that is tolerant of changing technology could mitigate obsolescence risk and generate LCC savings due to the higher-volume purchases and common maintenance and training. However, use of common FPD systems across platforms is rare. The Air Force Common Large Area Display Set (CLADS) program is currently considering LCC as a primary selection criterion.

For some applications, DoD is currently dependent on foreign FPD suppliers, but this dependency does not raise immediate vulnerability issues. DoD could face serious supply problems if domestic custom FPD suppliers are unable to stay in business.

Availability concerns pivot on [1] the potentially rapid obsolescence of commercial FPD products and [2] the economic viability of domestic custom FPD suppliers. Display integrators using commercial FPDs are working to establish long-term supply arrangements with foreign producers of displays, but it is unclear how responsive these relationships will be in the future. Some DoD display integrators using custom FPDs believe that until the FPD market matures and stabilizes, it would be imprudent for DoD to become dependent on foreign commercial FPD producers. However, many of these integrators are also concerned about the financial health of custom FPD producers in the United States. Relying on just the small volume of very demanding defense applications does not appear to be a viable business for the DoD domestic custom suppliers.

STANDARDS AND OPEN SYSTEMS

Few display integrators currently employ an open systems approach despite the potentially significant life cycle benefits of open systems.

Greater savings on the acquisition of FPD systems would be attainable if an open systems architecture were used. An open systems architecture uses common standards and interfaces that would enable the integrators to use off-the-shelf products. An open systems approach could also reduce costs and cycle time for redesigning and requalifying FPD systems. However, in the current budget environment, programs find it difficult to obtain the funding necessary for the non-recurring investments needed to implement an open system. Program offices also do not have resources available to monitor evolving commercial technology or to participate in standards development.

CONCLUSIONS

Given the importance of FPDs for meeting military needs, DoD will continue to spend significant resources for developing and acquiring FPD systems. The primary decision facing DoD is the extent to which individual programs are left to solve their particular applications and supply problems on their own, or whether cross-cutting investments and coordinating activities are needed to provide more effective results across DoD.

The FPD acquisition experience suggests that DoD's implementation of its acquisition strategy would benefit from greater focus on the problems of inserting a rapidly changing, dual-use technology into weapons applications. The objective of the National Flat Panel Display Initiative was to establish assured, affordable access to FPDs for military use through a dual-use supply base. While still valid, this objective remains unfulfilled.

Cross-cutting FPD efforts could better coordinate activities, mitigate supply uncertainty, and promote life cycle affordability. For instance, cross-cutting activities could:

- **Support programs in making sound technology choices**. Possible measures include active participation in non-governmental standards development, defense technology roadmapping, non-recurring engineering support for increasing commonality, coordinated testing of ruggedized displays, and continuing support for FPD technology development. Attention to adopting an open systems approach should be encouraged.
- **Continue development and expansion of the Integrated Process Teams approach**. Integrated mission planning, technology development, operational experiments, cost analysis, and training are particularly useful for investigating evolving technologies such as FPDs.
- **Address cross-program coordination needs.** The issues of assured supply, encouragement of commonality, and the upgrade and replacement of FPD systems over the life cycle of weapon systems require attention and leadership at a level above individual programs or Services.

While the study has focused specifically on the insertion of FPDs into defense systems, cross-cutting programs may also be able to foster commercial insertion of other emerging dual-use technologies into defense systems.

Part I
Introduction and Report Summary

1. OVERVIEW, FINDINGS, AND CONCLUSIONS

1.1 PURPOSE AND SCOPE

The Senate Armed Services Committee Report 105-29 on the National Defense Authorization Act for Fiscal Year 1998 requested that the Under Secretary of Defense for Acquisition and Technology (USD(A&T)) conduct a study of the acquisition of flat panel displays (FPDs) for military applications.[1] The Office of the USD(A&T) tasked the Institute for Defense Analyses (IDA) to conduct the study and established a Department of Defense (DoD) Steering Group to work with IDA to develop a work plan and oversee the effort.[2] On December 16, 1997, preliminary results of the study were discussed and refined at a workshop attended by a broad cross-section of the domestic FPD industry and DoD participants in FPD acquisition.[3]

The Congressional report raised specific concerns over how DoD program managers and their contractors, interacting with their sub-tier suppliers, have made tradeoffs in acquiring "consumer-grade displays designed primarily for laptop computers, which are then ruggedized for military use," rather than acquiring "FPD systems that are custom designed to meet military requirements." Further, because "quantitative data to support…cost and performance tradeoffs are not always readily available," program offices or contractors may not necessarily understand the consequences of reducing system requirements in order to acquire consumer grade components. The ultimate goal of this study was to provide weapon system program managers with data that would guide FPD system tradeoff decisions, "with the objective of meeting user needs at the lowest life cycle cost."

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1 Report with additional views from the Committee on Armed Services, United States Senate, June 17, 1997, p. 203. Full text is in Appendix C.

2 See Appendix D for a list of steering group members.

3 A summary of the workshop is given in Appendix E.

In addition to addressing these specific Congressional concerns, this report's findings provide some insight on DoD's progress toward its goals in Acquisition Reform and commercial technology insertion.

1.2 BACKGROUND

In the late 1980s, FPDs were an emerging technology that were becoming popular in watches, calculators, camcorders, and laptop computers. They also showed promise for military applications, but early FPD capabilities were insufficient for military combat needs. Therefore, DoD began to acquire FPDs for military applications using a traditional technology development approach. Programs that employed FPDs initially were combat systems that happened to be stressful applications in terms of environmental and performance.

The base to develop advanced FPD technology was U.S. research and development (R&D) organizations. Japanese manufacturers dominated the FPD business, and the United States had little production capability. In addition, R&D in advanced displays was funded by the Defense Advanced Research Projects Agency (DARPA) through its High Definition System Program.

DoD's focus on FPDs was given added impetus in 1994 with an assessment, *Building U.S. Capabilities in Flat Panel Displays*.[4] This report raised the concern that DoD's R&D in FPDs was not leading to FPD production capabilities supporting military applications. This led to the National Flat Panel Display Initiative (NFPDI) which was aimed at fostering the production and insertion of displays for meeting military needs. The NFPDI recommended a dual-use approach for meeting DoD's specialized needs rather than a unique, military-specific approach. Toward that end, key investments have been made in the following areas:

1. Manufacturing test-beds for domestic Active Matrix Liquid Crystal Display (AMLCD) production.

[4] *Building U.S. Capabilities in Flat Panel Displays*, Washington, DC: U.S. Department of Defense, October 1994.

2. Production incentive program to commercialize emerging FPD technologies.

3. Insertion program (using Title III provisions of the Defense Production Act) for reducing impediments for inserting FPDs into defense avionics.

4. Sustained investment in FPD R&D, including support for FPD infrastructure.

The NFPDI was targeted across the time spectrum. The manufacturing test-beds and insertion thrusts pursued near-term goals. The production incentive commercialization thrust was aimed about five years out, and advanced R&D was aimed at ten years out.[5]

1.3 STUDY APPROACH

As required by the Congressional tasking, this study focuses on:

- "Careful analysis of life cycle cost and performance tradeoffs to ensure that military needs are met."
- "Environmental and performance requirements and test data on performance of both custom and consumer-grade FPD systems in various military platform applications."
- "Life cycle cost and support issues such as commonality, supportability, and availability of both custom and consumer-grade FPD systems."
- "Potential benefits of FPD system interface standards and open systems approaches."

These issues are related to DoD's implementation of acquisition reform and commercial technology insertion. Acquisition Reform is transforming the defense acquisition process from the "how to" of military specifications and standards (Mil Specs) to a more flexible system emphasizing commercial-style business practices and

[5] Over $200 million has been spent on the NFPDI since 1994. However, this was about half the original amount called for by DoD in announcing the Initiative. A key element of this difference was the severe reduction in funding by Congress of the Technology Reinvestment Project, the primary mechanism for funding a second phase of the FPD production incentive program.

performance-cost tradeoffs. This study illuminates the processes and capabilities within the DoD acquisition environment for making the assessments and tradeoffs that are implied by this new way of doing business. DoD's primary interest is identifying what incentives support—and conversely what barriers and disincentives impede—decision makers in acquiring display systems with superior capabilities for military users, with reduced cycle times and at affordable costs (to buy and to own).

The study focuses on the elements of the analytical and decision processes that are entailed in display selection. The primary focal point is the decision-making processes of the display system integrator who provides the integrated display system to the weapon subsystem or system contractor. The integrator's decisions are affected by decisions of the prime and other higher-tier contractors. In addition, selection decisions are influenced by the program office in its requirements specification, contractual requirements, and its approach to cost-performance tradeoffs.

For this study the following definitions are used:

- "Consumer-grade" FPDs are manufactured in high volumes for use in consumer applications, particularly laptop computers. This report considers more sturdy FPDs, designed for automotive or industrial applications, as consumer-grade when they are produced in high volume for more than a single end product.
- "Semi-custom" are FPDs that are custom designed for a specialized application, but manufactured on the same production lines used to make consumer-grade FPDs.
- "Custom" FPDs are displays designed and produced for specialized applications, using production facilities that are oriented towards producing low volumes of special products.

Table 1 lists the specific tasks under taken to perform this study.

Table 1: Work Plan Tasks

Task 1	Define DoD use of FPDs to meet military needs.
Task 2	Define DoD acquisition practices and the procurement of FPDs.
Task 3	Provide an assessment of environmental and performance requirements and test data on performance of both custom and consumer-grade FPD systems in various military platform applications.
Task 4	Provide an assessment of life cycle costs and support issues such as commonality, supportability, and availability of both custom and consumer-grade FPD systems.
Task 5	Provide an assessment of the potential benefits of FPD system interface standards and open systems approaches.
Task 6	Prepare report of findings.

1.4 ORGANIZATION OF THIS REPORT

This report is divided into three parts. Part I, Introduction and Report Summary, provides the overview, findings and conclusions. Part II, Detailed Assessment, presents the analyses on which the findings and conclusions are based. Chapter 2 provides background on FPD technologies and markets. Chapter 3 describes the requirements for FPDs in different defense applications and how these are translated into performance specifications. Chapter 4 delves into how display system integrators select technologies and suppliers to meet these requirements. Chapter 5 discusses the type of test data available to support the necessary evaluations. Chapter 6 explores the life cycle cost impacts of FPD technology and depicts how life cycle cost considerations affect acquisition decisions. Chapter 7 covers the strategic issues of open systems, commonality across platforms, and long-term availability of FPDs. Chapter 8 contains the study's conclusions. Part III, Appendices and Supporting Data, contains the appendices, references, and acronyms.

1.5 FINDINGS

1.5.1 FINDINGS ON REQUIREMENTS

- FPDs, while a relatively new technology, are rapidly entering the DoD weapons inventory across a wide range of applications and missions.

- There are a large variety of FPD applications in defense systems, varying in performance and environmental requirements. The systems that displays are integrated into vary immensely with regard to cost, mission criticality, and other factors. There is no “one size fits all” solution.

- For almost every military application, the display system must be “ruggedized” in order to deal with shock, vibration, temperature extremes, and other environmental concerns. This ruggedization is typically accomplished through careful packaging and use of special adhesives, coatings, heaters, and seals. Measures such as these are required whether the display glass in the FPD system is consumer-grade or custom. In display systems using consumer-grade FPDs, the actual FPD glass is typically the only off-the-shelf part. Most other parts of the display assembly—e.g., backlights, filters, and electronics—are generally custom made.

1.5.2 FINDINGS ON MEETING REQUIREMENTS

- There are many different ways to meet military display requirements. The design of a display system involves technical choices at different levels of the system—FPD glass, optical components, laminations, electronics, and software—each of which can affect numerous display characteristics. The capabilities and options at each of these levels involve prime contractors, display integrators, and FPD suppliers in a variety of ways.

- Appropriately ruggedized consumer-grade FPDs can meet environmental and performance requirements for a broad range of military applications. Applications in which display systems using ruggedized consumer-grade FPDs have been selected include the following:
  - Naval shipboard command and control (C^2)
  - Armored and ground vehicles (but not tanks)

- Military transport aviation cockpits
- Soldier-portable computer systems

- If the display integrator is constrained by higher-level subsystem and system design decisions, there may be environmental and performance characteristics that are not possible to meet if using consumer-grade FPDs. This is a particular issue for combat avionics displays, which must [1] fit existing cockpit openings, [2] survive and operate at extreme temperatures, and [3] be readable in direct sunlight while still being compatible with night vision requirements.

- In the past, custom AMLCD producers had major difficulties meeting schedules for products achieving initial performance specifications. Display integrators and primes reported that the inability to obtain FPDs on schedule cost them “tens of millions of dollars.” Currently, domestic custom FPD producers are meeting delivery schedules for defense contracts.

- These initial problems in acquiring display systems using custom FPDs drove certain programs and contractors to seek alternative sources. Some programs determined that lesser capabilities were acceptable to meet the user’s needs and allowed the use of ruggedized consumer-grade FPDs.

1.5.3 FINDINGS ON TESTING CONSUMER-GRADE AND CUSTOM FPDS

- FPDs are qualified by individual vendors against contracted environmental and performance requirements. Thus, there are extensive program-specific test data on selected consumer-grade and custom FPDs integrated into military systems.

- Because FPD performance test data have generally been collected only for particular situations, programs have reached different judgments about the environmental tolerance and performance of ruggedized consumer-grade FPDs.

- Test data are generally viewed as proprietary by the FPD integrator and hence are not made available across programs or to other contractors. Programs have adopted “lessons learned” from other programs only on a limited and *ad hoc* basis. Lacking credible characterization, some programs have been reluctant to use consumer-grade FPDs.

- When products were not able to affordably meet performance requirements, some programs accepted lesser FPD performance. Concerns have been raised that these decisions have been made without sufficient study of the mission consequences. There appear to be few systematic assessments of the impact of display performance on mission effectiveness. Such analyses would be valuable in making performance, cost, and schedule tradeoff decisions.

- A few comparative assessments have been made of the ability of different FPD products to meet particular mission requirements. A study of FPDs for transport aviation showed wide variation in the level and quality of ruggedization, and that some ruggedized consumer-grade FPDs, as well as already available custom FPDs, can meet the performance requirements of transport aviation. Other comparative evaluations of consumer-grade FPDs have been performed on combat aircraft (F-16), C^2, and Army ground vehicles (Appliqué).

1.5.4 FINDINGS ON LIFE CYCLE COST

- FPD-based display systems reduce ownership costs in a variety of platforms and missions. Reliability is particularly important. FPD systems, whether custom or ruggedized consumer-grade, are typically ten to twenty times more reliable than the cathode ray tube (CRT) systems they replace. This study did not uncover data that indicated any further reliability advantage in using custom vs. consumer-grade FPDs.

- Programs are motivated to introduce FPDs in order to reduce life cycle costs (LCC) while at least maintaining the performance for their platform (especially compared to CRTs), as well as the costs associated with carrying out their missions.

- This study did not find any programs where the LCC of a proposed FPD system was a primary selection criterion for choosing between FPD alternatives. Programs were typically concerned more with initial acquisition cost than with LCC. The highly competitive and budget-constrained environment in which most programs currently find themselves encourages immediate, concrete savings over uncertain life cycle savings. One program, the Air Force Common Large Area Display Set (CLADS), is currently considering LCC as a primary selection criterion. The Abrams display program has also given specific attention to LCC in its assessments.

- Programs acquiring FPDs that correspond to standard commercial sizes can typically realize initial acquisition cost savings by employing consumer-grade FPDs. Direct comparisons are difficult because programs do not use common FPD systems. However, rough cost estimates were provided to this study for the front end of an avionics display or "display head"—the FPD, backlight, and drive electronics but no processing electronics. The procurement cost of a display head employing a custom FPD was typically about 30 to 50% higher than one using a consumer-grade FPD. Future replacement costs of a custom display could be much higher.

- Replacement costs have been raised as a potential issue in the use of consumer-grade FPDs. The claim is that over a weapon's life cycle, ruggedized consumer-grade FPDs could be more expensive than custom FPDs due to rapid commercial product obsolescence. Changing the FPD used in a system could require costly redesign and qualification if it is not available at the time it is needed. While this may be true, this must be balanced against the higher development and procurement costs of custom FPDs that are also vulnerable to obsolescence.

1.5.5 Findings on Strategic Issues: Open Systems, Commonality, and Availability

- Greater savings on the acquisition of FPD systems would be attainable if an open systems architecture for display systems was used. An open systems approach could also reduce redesign costs. However, such management and design practices are not the norm today.

- Commonality using a design that is tolerant to changing technology across programs would allow savings due to higher volume purchases and common maintenance and training. However, use of common FPD systems across platforms is rare.

- Availability concerns pivot on [1] the potentially rapid obsolescence of commercial FPDs and [2] the economic viability of custom FPD suppliers.

- Concerning the potentially rapid obsolescence of commercial FPDs:
  - The display integrators who were using consumer-grade FPDs were not especially concerned about availability. The greater Mean Time Between Failure (MTBF) of FPD systems should make the need for replacement rare. If resupply is needed, their experience has been that older FPD products have continued to be available for extended periods, and that the foreign manufacturers with whom they have worked have either made alternative products available or provided sufficient notice for lifetime buys to be arranged.
  - Display integrators who are using foreign-sourced FPDs are working to establish long-term, responsive supply arrangements. Today there are few of these arrangements and it is unclear how responsive these relationships will be toward meeting future defense needs.
  - Several DoD display integrators supplying advanced combat systems believe that until the FPD market matures and stabilizes, it would be imprudent for DoD to put itself in a position of being dependent solely on foreign, commercial FPD producers.
    * The current supply arrangements that certain display integrators have with foreign FPD producers are possible only because avionics FPD systems are considered "dual-use" products because they are predominantly used in commercial aircraft. This dual-use arrangement does not apply across the spectrum of DoD needs.
    * In the future, due to changing market conditions and FPD industry capacity, commercial FPD producers may no longer be responsive to DoD needs.
    * Considerable time and additional resources would be required to re-engineer existing custom display applications to accommodate consumer-grade FPDs or customized FPDs made by commercial producers.

- Economic viability of custom FPD supplies:
  - Combat system military display integrators are concerned about the financial health of domestic custom FPD producers. Relying on just the small volume of very demanding defense applications does not appear to be a viable business for the DoD domestic custom suppliers.

– One key uncertainty is the future of FPD technology. Several new approaches—most notably Field Emission Display (FED) technology—potentially could be used in many applications. It will likely be at least three to five years before the commercial future and military value of these technologies is known. Moreover, time and resources will be required to develop, test, and qualify these new technologies for military applications.

1.6 CONCLUSIONS

The objective of the NFPDI was to establish assured, affordable access to FPDs for military use through a dual-use supply base. This objective is still valid but has not yet been achieved. Custom vendors have succeeded in developing FPDs that meet the most stringent DoD requirements, but they have not established their businesses as viable, dual-use suppliers. One display integrator has established a relationship with a commercial FPD vendor to have custom FPDs manufactured on a commercial line for dual-use avionics applications. It is unclear whether efforts by other display integrators to create similar relationships will be successful. The increased capabilities of ruggedized consumer-grade FPDs have made them both more accessible and affordable for less demanding defense applications, but life cycle issues concerning upgrade and replacement due to obsolescence have not been adequately addressed.

DoD program managers and their system integrators have creatively managed the near-term issues involved in inserting FPDs, though with some cost, schedule, and performance impacts. The issue facing DoD today is how to most effectively allocate its resources to obtain assured, affordable access to advanced FPD technology. Given the importance of FPDs for meeting military needs, DoD will continue to spend significant resources for developing and acquiring FPD systems. **The primary decision facing DoD is the extent to which individual programs are left to solve their particular applications and supply problems on their own, or whether cross-cutting investments and coordinating activities are needed to provide more effective results across DoD.**

FPD acquisition demonstrates the effectiveness of Acquisition Reform in providing programs with the flexibility to meet their needs using available commercial technology. However, system integrators have raised concerns that “best value” contracting, given the lack of attention to LCC, often appears to be simply lowest initial acquisition cost, not a tradeoff between LCC and performance. This study’s findings on LCC suggest that this may be a valid concern and requires further attention.

More broadly, effective life cycle management for an evolving technology such as FPDs requires attention and leadership at a level above individual programs or Services. The FPD acquisition experience suggests that DoD's implementation of its acquisition strategy has not adequately addressed the problems attendant with inserting a rapidly changing, dual-use technology into weapons applications (e.g, non-recurring engineering and qualification costs).

Cross-cutting FPD programs and coordinating activities could mitigate supply uncertainty and promote life cycle affordability. DoD should consider the following measures:

- **Support programs in making sound technology choices**. Possible measures include active participation in non-governmental standards development, defense technology roadmapping, non-recurring engineering support for increasing commonality, coordinated testing of ruggedized displays, and continuing support for FPD technology development. Attention to adopting an open systems approach should be encouraged. These activities should be funded and conducted as a coordinated, integrated effort.
- **Continue development and expansion of the Integrated Process Teams (IPTs) approach**. IPTs can help prevent both overspecification, leading to high LCC, as well as underspecification, leading to constrained future development and flexibility. With advances being made in an array of FPD technologies, driven largely by the commercial market, DoD needs to develop an acquisition strategy for displays that does not lock it into any particular technology. Integrated mission planning, technology development, operational experiments, cost analysis, and training—i.e., "learning by doing"—are particularly useful for investigating evolving technologies such as FPDs. The IPT process can enable consideration of trade-offs over the system's life cycle, and can also provide early insight into new technologies, which can then contribute to open standards development.
- **Address cross-program coordination needs**. The issues of assured supply, encouragement of commonality, and the upgrade and replacement of FPD systems over the life cycle of weapon systems require attention and leadership at a level above individual programs or Services. At present, there is no higher-level organization within DoD responsible for addressing crosscutting FPD concerns. The recently proposed Radiation Hardened Electronics Oversight Council may be a model for coordinating technology investment and acquisition.

Part II
Detailed Assessment

2. FLAT PANEL DISPLAY TECHNOLOGIES AND MARKETS[1]

Flat panel display (FPDs) are thin electronic devices used to create visual images or present textual information. They are used in handheld TVs and games, laptop computers, and as readouts for industrial, automotive and medical equipment. FPDs have evolved over the past thirty years from simple devices capable of showing only simple output, such as alphanumeric readouts for digital watches and calculators, to highly advanced video systems for a wide range of applications. The most advanced FPDs are capable of displaying full-color, high definition images at full video rates. In certain respects, these advanced FPDs have superior viewing characteristics when compared to cathode ray tubes (CRTs), the currently dominant technology for display systems. However, different FPD technologies provide not only different characteristics, but have different strengths and weaknesses. The CRT is a mature and inexpensive technology compared to FPDs, and they still account for over 95 percent of all television and computer desktop displays. However, CRTs are bulky, heavy, high in power consumption, and relatively fragile. These characteristics make them unattractive for use in portable electronic systems, such as handheld TVs and laptop computers.

2.1 FPD TECHNOLOGIES

An FPD can be implemented using a number of technical approaches. The dominant FPD technology today is the liquid crystal display (LCD). Other FPD technologies include electroluminescent displays (ELDs), plasma display panels (PDPs), field emission displays (FEDs), and rear projection displays.

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1 This section abbreviates and updates a similar presentation made in the report, *Building U.S. Capabilities in Flat Panel Displays*, Department of Defense, October 1994.

2.1.1 LIQUID CRYSTAL DISPLAYS

The most prevalent FPD technology today is the liquid crystal display (LCD). A typical LCD "display head" configuration is pictured in Figure 1. The display head consists of four major subassemblies:

- **Liquid crystal (LC) cell**, consisting of a thin-film transistor (TFT) substrate, color filter substrate, and liquid crystals.
- **Laminations placed on the LC cell**, consisting of polarizers, retarders, heater glass, cover glass, adhesive, and electromagnetic interference (EMI) shield.
- **Driver assembly**, consisting of row and column drivers, interface electronics, and mechanical packaging.
- **Backlight assembly**, consisting of diffusers, backlight cavity, fluorescent lamp, and lamp drive electronics.

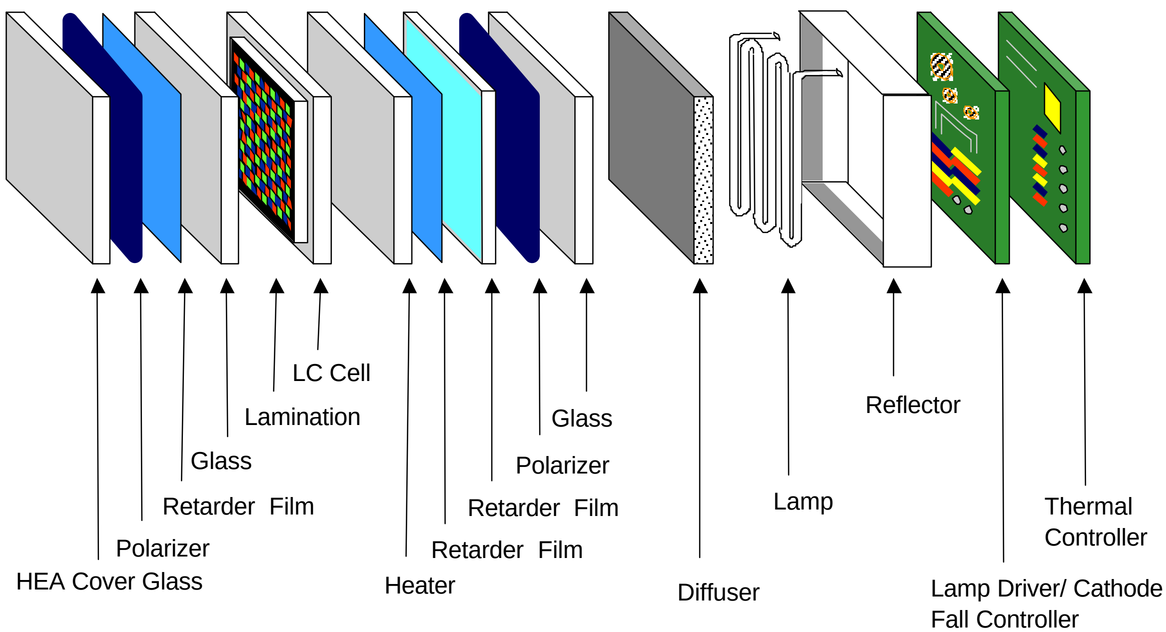

Figure 1: A Typical LCD Display Head

To form an LC cell, a polarizing film is deposited on the outer surfaces of two ultra-flat glass or quartz substrates, and a matrix of indium tin oxide (ITO) electrodes is deposited on the inner surfaces of these substrates. Using micron-thin spacers to hold the substrates apart, they are joined together in a "sandwich." The two substrates are then sealed with a gasket, the interior air is evacuated, and the void is filled with liquid crystals. Liquid crystals are organic polymers that respond to an applied voltage. Various laminations are attached to the LC cell in order to achieve desired optical properties.

This LC cell and laminations are placed in front of a light source (the backlight assembly) and integrated with driver electronics to make a display head. The usual light source is a metal halide, cold cathode, fluorescent or halogen bulb. To provide the desired brightness for the display, the wattage of the light source must be sufficient for light to pass through polarizers, glass, liquid crystals, filters, and electrodes. The internal complexity of the LCD blocks as much as 95% of the light. As a result, the generation of unseen light is a major drain on the LCDs power source.[2]

Images are created by controlling the voltage at specific positions on the display surface. When no voltage is applied, the liquid crystals are aligned in such a way that light can pass through the polarizer, thus illuminating the viewing surface. When a voltage is applied to particular locations, the liquid crystals twist in order to align themselves to the electric field. This twisting changes the polarity in such a way that light cannot pass through, and the viewing surface appears dark.

Over time LCDs have become increasingly complex in order to improve their performance. Early LCDs were passive devices with a set of closely spaced, transparent horizontal electrodes on one plate and vertical electrodes on the other. Voltages on these row and column electrodes combine at their intersection to turn on a pixel at that point. These passive LCDs were relatively easy to produce, but they were also comparatively slow, with the slowness of operation increasing with size. Therefore an alternative approach, the Active Matrix Liquid Crystal Display (AMLCD) has gained popularity for higher performance and larger displays.

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[2] Improving the transmissivity of the LCD is one area of technical advance where LCD producers compete. Better transmissivity reduces power consumption and increases brightness. An alternative to the back-lit LCD is the reflective LCD which uses reflected external light as the source of illumination.

The AMLCD typically uses thin-film transistors (TFTs) at each pixel to control its off-on state. TFTs are made in a manner similar to integrated circuits. To make an AMLCD, the front transparent electrode is deposited over the glass surface to serve as a ground electrode. On the rear glass, a matrix of transistors is deposited along with metal interconnect lines. (At least three transistors per pixel are required to produce color.) The quality of AMLCDs is driven largely by the ability to produce a near-perfect matrix of TFTs across the glass substrate. As the size of the substrate increases, the difficulty of achieving zero-defects in the transistor process becomes greater.[3]

2.1.2 ELECTROLUMINESCENT DISPLAYS

Electroluminescent displays (ELDs) are emissive displays: they generate their own light, rather than acting as a light switch. The light is generated by a phosphor material sandwiched between front and back electrodes. There are passive and active addressing schemes for ELDs, similar to those for LCDs. Monochrome ELDs are used today in military applications, financial and ATM machines, and in industrial displays for medical, process control, test, and analytical equipment. Thin-film ELDs have been used widely in military applications where performance is required over a wide temperature range. ELDs have only recently achieved full-color capabilities due to difficulties producing phosphors with high brightness and good color saturation (particularly for blue colors).

2.1.3 PLASMA DISPLAYS

The largest direct view FPDs available are plasma display panels (PDPs). PDPs consist of a front and back substrate with phosphors deposited on the inside of the front plate. The display has cells that operate similarly to a plasma or fluorescent lamp: the discharging of an inert gas between the glass plates of each cell generates light. To obtain color, more complex phosphors are required. Compared to other FPD

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[3] For most AMLCDs, the TFTs are made of amorphous silicon, a-Si, deposited on a glass substrate. R&D is being conducted on polysilicon and single crystal silicon to achieve faster transistors. These both require a higher temperature substrate to produce so quartz is used rather than glass, which further increases their cost. Today this limits the use of poly- and single crystal silicon to small and very specialized applications.

technologies, PDPs have relatively simple structures and relatively low manufacturing cost, but they have relatively high power consumption and require high voltage drivers. Plasma displays are particularly attractive for applications requiring large-area, high-resolution displays.

2.1.4 FIELD EMISSION DISPLAYS

Field emission displays (FEDs) are solid-state vacuum displays that operate similarly to a CRT but in miniature. FEDs are based on the cold emission of electrons from an array of metal or semiconductor microtips or other emitting surfaces. Microtips are extremely small cones that serve as cathodes. Hundreds or thousands of microtips are used for one pixel, providing redundancy. An anode voltage accelerates electrons from the cathode through a grid structure to the anode. The electrons activate phosphors at the anode to produce light. FEDs are just now entering into production.

2.1.5 PROJECTION DISPLAYS

Liquid crystal displays are currently available with diagonal sizes up to 21” and PDPs can be purchased at sizes up to 42”. Slightly larger panels have been produced as prototypes, but even at the top of the range of commercial products, the price is high. An attractive alternative of creating large high-definition images is through the use of projection systems. Projection technology is moving towards the use of relatively small light modulators, such as polysilicon AMLCDs or devices built upon silicon chips, such as the Digital Mirror Device™ from Texas Instruments. There are now several such devices that can create full color images with up to 2,000 lines on modulators less than 2” in size. With a powerful compact light source, these images can be projected onto large screens. Rear screen projection systems, with panels sizes from 19” to say 80”, are suitable for command and control applications, provided that the projection optics can withstand the vibration and shock conditions. Front view systems are ideal for simulation purposes. The new projection technologies are less advanced than the FPDs for notebook computers, but the current rate of progress is impressive and U.S. industry is pioneering much of this development.

2.1.6 OTHER DISPLAY TECHNOLOGIES

Several other technologies are contending for the FPD market. Light emitting diodes (LEDs) were an early competitor that did not advance into high information content applications. However, recent advances in organic LEDs show promise for use in flexible displays. Vacuum fluorescent displays (VFDs) are inexpensive, low-resolution displays which serve niche markets such as instrumentation and small consumer displays.

2.2 COMMERCIAL AND MILITARY FPD MARKETS

The size of the FPD market in 1997 was about $14 billion. It is projected to reach $20 billion by the year 2000, with a compound annual growth rate (CAGR) of about 15 percent. AMLCDs are the dominant FPD technology, with almost 60 percent of the market. Passive LCDs made up about 25 percent of the global FPD revenues in 1997. By 2000, AMLCDs are expected to make up approximately 65 percent of the market, and passive LCDs to fall below 20 percent of the market. In 1997 the relative shares of other FPD technologies were each under 10 percent.

Today laptops constitute over 60 percent of total FPD consumption by revenue. Other categories of FPD consumption are hand-held devices (personal digital assistants, digital cameras), telecommunications, car navigation, games, and industrial applications. The total revenues for these categories are about $2.5 to 3 billion. It is expected that the size of these other markets will double within three or four years. Two emerging consumer segments are computer and workstation monitors and high-definition wall-mounted television monitors. These are large format applications: from 14-inch diagonals to up to 50 inches. Today this market is under $500 million, but market analysts project it to reach over $3 billion by 2000, and $7 billion by 2002.[4] AMLCD, PDP, FED, and DMD projection technologies are contenders for such

[4] Derived from market forecast briefings. Prices for FPD monitors are currently two to three times those of CRT monitors. Projections of future penetration of FPDs into the desktop computer market assume a convergence on price in which the FPD price would be about 10% higher than a comparable CRT by around 2002. For example, see Ross Young, *LCD Technology and Market Forecast*, presentation to Display Works98, January 20, 1998.

applications. Another emerging opportunity is "virtual reality" head-mounted applications.

AMLCD technology has a major advantage over alternative technologies in that it has a large and growing global manufacturing base comprised of many large-volume commercial producers and a multi-billion dollar industrial revenue stream that funds R&D in the technology. Competition serves continually to drive down costs, making it increasingly difficult for new technologies to compete. However, this commercial production base is generally dedicated to meeting high-volume production of a small number of display designs. Thus, such facilities are not easily or profitably available for producing specialized displays such as those used in military combat avionics. The issue of accessing high-volume production lines versus building custom displays in special production facilities is central to the concerns over tradeoffs between consumer-grade and custom displays.

Until recently, the CRT has been the primary technology "for military and avionics displays requiring high-resolution monochrome and color video performance together with flight and tactical symbology."[5] Flat panel displays have begun to displace CRTs for these applications as limitations of FPDs in resolution, gray- scale range, viewing angle, and overall visual quality have been resolved. The first military use of FPDs was in low-information content applications such as warning indicators. The earliest use of a high-information content FPD in a combat aviation cockpit was the F-117 in the late 1980s. Beginning early in the 1990s, several aviation programs, both combat and transport, began to actively pursue development and use of AMLCDs.[6] In addition, FPDs are being integrated into naval systems for use in combat systems. For example, in the New Attack Submarine, there is a need to bring together both navigation and situation awareness information and present the warfighters with appropriate

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5 Van Angelo, "Comparison of Custom vs . COTS AMLCD's for Military and Avionic Applications," SPIE 3057, 1997, pp. 52-59.

6 Darrel G. Hopper, "Flat Panel Cockpit Display Requirements and Specification," Advanced Flat Panel Display Technologies, Vol. 2174, Paper 9, International Society for Optical Engineering, 1994, pp. 2-12. The Joint Cockpit Office at the Air Force Wright Patterson Laboratory has played an active role in supporting the development of AMLCDs for use in aviation cockpits.

resolution on a large-screen (approximately 30-inch diagonal).[7] The largest area of potential military demand is for soldier-mounted systems. While demonstration and small-scale applications are scheduled for soldier-mounted systems, such systems will not be fielded in significant numbers for several years.

Military applications make up a very small portion of overall demand. For instance, the overall demand for soldier systems will be in the thousands of units per year in contrast to the millions of commercial FPDs sold per year. Currently, worldwide demand for military FPDs is about $100 million per year. However, the total value of systems incorporating FPDs is much larger and makes for an attractive business for military suppliers. A line replaceable unit (LRU) for a military avionics display or situation awareness system—including the integrating and interface electronics, application software, and mechanical housings—costs from $20,000 to several $100,000. A display head assembly can range from $2,000 up to $20,000, depending on its size and functionality. At these prices, subsystem vendors can target an overall business totaling several hundred million over the next few years. This military business involves very low volumes with several different vendors competing. A firm providing military display LRUs, whether as an independent company or a division of a larger firm, typically has annual revenues in the range of $20 million to $50 million per year.

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7 Erik Chaum, "Joint-Service Electronic Map / Chart (JEMC) Display," Newport, RI: Naval Undersea Warfare Center, paper presented to the DARPA Joint Large Display Working Group, May 6-7, 1997.

3. DEFENSE REQUIREMENTS FOR FPDS

3.1 INTRODUCTION

While a relatively new technology, FPDs, are rapidly entering the DoD weapons inventory across a wide range of applications and missions. DoD's interest is driven by their advantages in size, weight, durability, performance capabilities, and by life cycle cost savings relative to CRTs. FPD-based display systems are lighter, consume less power, and take up less space than CRT-based systems (i.e., traditional TVs and monitors). Replacing bulkier, less-robust CRTs with FPDs has been a major area of military insertion. FPDs are also being introduced onto platforms that do not have room for a CRT. For example, an FPD system is being acquired to provide navigation and situation awareness information in the Army's Bradley Fighting Vehicle which has no room to house a CRT-based system. Finally, the flat form factor and relative ruggedness of FPDs have made the introduction of display systems feasible for portable military applications, just as FPDs made laptop computers possible.

Advances in the performance of LCDs have been accomplished primarily with a view toward improving the quality of laptop computers. Laptops are typically viewed by a single user in a controlled environment. The contents of the screen cannot be viewed outside on a sunny day and works poorly, if at all, at temperatures below freezing. Damage to, or failure of, a laptop display represents a major inconvenience, but is rarely, if ever, life threatening. Nevertheless, few travelers would consign notebook computers to their checked baggage.

Military use of FPDs has two stressing features relative to more common uses of FPDs, such as laptop computers:

1. Extremely harsh operating environments and
2. Extremely demanding optical performance characteristics.

Concerning the first point, military displays are used in a wide variety of environments, some of which are predictable while others possess a large degree of uncertainty. Almost all applications must allow for environments far harsher than those experienced by laptop displays, and the cost of failure is often high. For almost every military application, the display system must be "ruggedized" in order to deal with such stresses as shock, vibration, temperature extremes, high humidity, salt fog and electromagnetic emanations. This ruggedization is typically accomplished through careful packaging and use of special adhesives, coatings, heaters, and seals. Mechanical protections such as these are required whether the display glass in the FPD system is consumer-grade or custom. Thus, truly "commercial-off-the-shelf" FPD systems are almost never suitable for direct insertion into a weapons platform. In display systems using consumer-grade FPDs, the LC-cell is typically the only off-the-shelf part. All other parts of the display assembly—e.g., backlights, filters, and electronics—are usually custom made.

Military applications typically also call for display systems with special optical performance properties that differ from those available in consumer-grade products. These include especially wide or narrow viewing angles, high resolution, high brightness for sunlight readability, specific color characteristics, low reflectivity, extreme dimming for compatibility with night vision equipment, and other special characteristics. In legacy systems, a display system frequently must be of a certain size and shape to fit an existing "hole." [8]

3.2 HOW THE EMERGING FPD MARKET DRIVES CAPABILITIES

FPDs were first developed in the research laboratories of organizations such as RCA, General Electric, and Westinghouse, with commercial television as the main focus.[9] In these early developments, the companies and DoD recognized that FPDs could offer (1) direct mission advantages in terms of providing functional capabilities in harsh

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8 The specific requirements for environmental protection and enhanced performance, and the means for meeting these for FPD systems, are discussed in detail in Appendix A of this report.

9 General Electric and Westinghouse both received R&D funds from the Air Force starting in the late 1960s for LCD technology.

military environments, and (2) secondary cost advantages due to reduced weight, size, and power consumption.

However, it was also seen that considerable investment would be needed before the capabilities of this emerging technology could successfully be integrated into military systems. When large consumer product firms, such as RCA, GE, and Westinghouse, exited the consumer television market, their interest in pursuing FPDs largely evaporated. But military interest in harnessing the potential capabilities of FPDs continued.

The initial factors driving this interest in FPDs were their potential technical capabilities, such as intrinsic ruggedness and compactness, when compared to existing CRTs. This interest increased as available sources for military-specialized CRTs diminished and their prices escalated. CRT-based military displays were generally customized in order to provide the performance needed in harsh military environments. Even when built as military-specialized devices, CRT displays had reliability problems and were becoming a major concern from a life cycle cost standpoint. Moreover, there were growing needs to find a more compact display solution for embedded displays in military systems, such as aviation cockpits. Bulky CRTs took up too much scarce space in cockpits. FPDs offered the prospect of obtaining the same or better functional performance in two rather than three dimensions, allowing space in the cockpit to be used much more efficiently.

Another factor driving the interest in FPDs has been the need to provide greater information to the combat system operator. Displays were seen as an intrinsic part of the overall combat information system. For example, the drive toward reduced manning is placing more emphasis on information and electronics capabilities that provide greater functionality to the user. These demands, in turn, increase the requirements being placed on military display systems. FPDs provide the potential to integrate the display and the electronics processing to achieve functional capabilities that cannot be provided by CRTs.

3.3 REQUIREMENTS IN A DYNAMIC ENVIRONMENT

Setting "requirements" for a new and changing technology such as FPDs is itself a dynamic process. When setting the first requirements for FPDs, the system engineers for program offices and contractors had little direct experience with FPDs, and they often used the CRT as the basis for determining technical performance characteristics.

There are certain levels of performance that the FPD must meet to be accepted—for example, from a pilot's viewpoint, he wants an FPD to perform at least as well as the CRT it is replacing. Yet translating this objective into a measurable specification can be very difficult, given that the technologies are so different. Measures applicable to the performance of a CRT may not apply to an FPD. In addition, there are certain performance features that are intrinsic to a CRT, such as a nearly 180-degree viewing angle that can not be readily achieved by certain types of FPDs (especially LCDs). In this case, the "requirement" is often set at achieving a certain minimum level, commonly a level stressing the existing state of the art. As FPD technologies improve, it is reasonable to expect that "requirements" will be redefined to take advantage of these better capabilities.

Yet making appropriate tradeoffs between performance and cost can often be difficult. One example is the requirement for brightness of an FPD so that it can be read in a glass or bubble canopy of a combat aircraft. Initial requirements were set at 200-foot lamberts that stressed known technology. However, when FPDs with this level of illumination were flight tested, the pilots stated that the displays needed to be considerably brighter. While technically achievable, increasing the brightness to this extent places many other demands on the display engineering, including issues of heat, power consumption, dimming, etc., many of which are system-level concerns.

This example highlights how system-level considerations affect the setting of display requirements. Requirements set at levels above the subsystem, often constrain the display options available. Systems designers usually budget space, power, weight, and other aspects of the system over many subsystems. Once these are set, it can be very difficult to get them reconsidered, particularly after the initial decision process is completed, even if what seems to be a minor compromise might make very large differences in cost and schedule. Redefining such requirements is difficult for a new system being developed from scratch, such as the F-22.[10] For existing systems that are being upgraded or retrofit, the constraints are even greater. In such instances, size, electrical interface, and other constraints can be extremely limiting. Sometimes the demands on the system are driven by legacies, such as the symbology for an aviation display originally designed for a CRT, that have to be accommodated in the FPD. Because this symbology has proliferated throughout the avionics software, it would be very costly to revise. The military display engineer is then faced with the difficult task of making these incompatible symbols work on the FPD.

In defining requirements for an emerging technology such as FPDs, it is not unusual for initial specifications to be changed when it is found that they are either inadequate, cannot be met, or only can be met at excessive cost or time. In early FPD insertion programs, such as the F-22 or the C-130H, no existing FPDs—custom or consumer-grade—could meet the originally conceived requirements. When some programs concluded that the initial performance requirements were not achievable, they determined that lesser capabilities were "acceptable" and granted waivers. This practice has raised issues regarding the contracting process. What some specialized FPD providers regard as an abrupt, and perhaps unfair, change in the process, is seen by others as being a realistic shift in fielding systems using a "best value" approach. However, prior to the production phase, DoD contracts normally contain a change-order clause to accommodate modifications due to such factors as unanticipated cost, availability, or technology changes. Given earlier experiences where stated FPD requirements were not achievable, there is recognition that care must be taken to state requirements that are "achievable" within reasonable cost. This issue of the tradeoff between "requirements" versus cost is further discussed in Chapter 6.[11]

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10 See Appendix B for a discussion of FPD insertion into the F-22.

11 Interestingly, Boeing's commercial division has experienced many of these same phenomena in the FPD development effort for the 777's. It is presently considering relaxing certain specifications in order to achieve greater production yields. See Appendix B for a discussion of insertion of FPDs into the Boeing 777.

3.4 ENVIRONMENTAL AND PERFORMANCE REQUIREMENTS FOR MILITARY FPDS

A major consideration in setting requirements is the information that is to be displayed. For example, important performance demands are placed on some military displays by the need to show night vision and other sensor data. The types of information to be displayed and the environment in which the information must be shown place requirements on military displays that go well beyond those for commercial FPDs. Consumer-grade AMLCDs have pixel arrays consistent with television video sources or one of the *de facto* laptop, desktop, or workstation computer standards for graphics displays.[12] Only two pixel structures are available (delta configuration for television and vertical stripe triad for computer screens). Some advanced military displays, such as those used for combat situation awareness and weapons targeting, require a multifunction capability in order to show color symbology, digital map data and low light television video, and monochrome forward looking infrared (FLIR) video and radar data. This data comes from various sources with different line structures, but all must be displayed with a high degree of resolution without visual aliasing artifacts. The approach usually taken to accommodate these requirements is to use application-specific pixel arrays and specialized pixel structures, such as a quad pixel configuration, that differ from consumer-grade products. Pixel configurations for sizing and resolution cannot be retrofitted into an existing LCD glass and, thus, have driven the use of custom FPD glass.

The requirement for environmental protection and performance for military displays vary depending upon application. These differing requirements call for special characteristics in the engineering of particular display solutions. Table 1 lists currently defined FPD requirements for the environmental categories generally of concern to defense users.[13] The following sections discuss these requirements in more detail for different military applications. In Appendix A, environmental and performance categories are elaborated with specific attention given to measures for their achievement.

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12 The resolution of a display is defined by the pixel configuration. The most common pixel configuration for a consumer-grade FPD currently is 800 x 600 pixels.

13 Angelo, Van, “Comparison of Custom vs. COTS AMLCD’s for Military and Avionic Applications, SPIE, 3057, p. 53.

Table 1: FPD Environmental Requirements by Military Application

Parameter	Combat Aircraft/ Army Vehicles	Support/ Surveillance Aircraft/ Vehicles	Command Posts	Soldier Portable Terminals	Commercial Transport Aircraft
Operating Temperature	-40° to +71° C	-20° to +55° C	+0° to +45° C	-40° to +55° C	-40° to +55° C
Humidity/ Salt Fog	to 100%	to 100%	to 90%	to 100%	to 95%
Shock	to 30g[14]	to 15g	to 2g	to 30g	to 11g
Vibration	Severe Gunfire	Sustained	Low	Low	Sustained
EMI[15]	200 v/m	50 v/m	Low	Low	20 v/m
Illumination	to 10,000 fc	3,000 - 8,000 fc	<1,000 fc	to 8,000 fc	to 8,000 fc

In depicting military requirements, it is useful to understand the key features of these different military applications, including avionics, ground combat vehicles, surface ships and submarines, soldier-portable displays, and command and control systems. Each application is discussed in further detail in the following section.

3.4.1 AVIONICS

FPDs have been used in many different military avionics applications. The need to better inform the pilot of his aircraft's performance and provide him information regarding his mission and situation spurred the use of FPDs. Generally the avionics system is an "embedded" system, meaning that it is integrated into the aircraft's flight instrumentation and mission control systems. The military cockpit is very space constrained and the conditions within the cockpit are very harsh.

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14 One 'g' corresponds to an acceleration equal to earth's gravity, and 30g's is hence an acceleration level corresponding force equal to 30 times earth's pull.

15 Electromagnetic interference (EMI) is a measure of voltage field fluctuations which can cause noise and interference in equipment. It is measured as a voltage drop over distance (v/m).

One of the most trying aspects of a cockpit, particularly for glass (bubble) canopy fighter aircraft, is sunlight readability, with the sun shining into the pilot's eyes and onto the flight instrument itself. The cockpit has both very bright ambient illumination (8,000-10,000 foot candles (fc)) and ambient reflections of 2000-3000 foot lamberts (fL). In addition, unless special compensating measures are taken, AMLCDs also create specular reflections which further reduce visibility. Key to sunlight readability is achieving high luminance while maintaining a minimum contrast ratio. To provide sunlight readability, custom AMLCDs intended for glass canopy applications incorporate anti-reflection features in the liquid crystal cell itself.

Sunlight readability must be achieved while simultaneously being able to provide variable brightness in order to accommodate night operations and the highly specialized characteristics for use of night vision goggles. The design of FPDs for military applications requires tradeoffs be made between desired capabilities, which often can place competing demands on the system.

Acceleration, vibration, and shock requirements clearly vary, with the severest conditions anticipated for agile fighters and combat helicopters. Transport and reconnaissance aircraft usually are not subjected to such high stresses. Combat aircraft must be operable at short notice, so that short warm-up times and wide operating temperature ranges are needed.

3.4.2 GROUND COMBAT VEHICLES

The performance and environmental requirements for military land vehicles vary widely. Temperature and ambient illumination requirements are severe for most combat vehicles. The ability to withstand vibration and shock stress is important. The degree of protection needed depends on the combat mission type (heavy armored, direct combat vs. light armored, combat support) and the need to operate continuously while being hit by enemy fire and under nuclear, biological and chemical threats The Abrams M1A1 tank must be able to perform its mission in very harsh conditions. The environment and performance needs of the Bradley fighting vehicle are somewhat less severe, and personnel carrier requirements are less still. The Abrams is now going through an upgrade to provide the tank commander with capabilities to display full-color topographic maps and improved infrared battlefield display capabilities.

Similarly, the Bradley is building the M2A3 with displays capable of showing digital map information and sensor data imagery.

3.4.3 SURFACE SHIPS AND SUBMARINES

Mechanical shock is the major environmental issue for the Navy. The display unit is part of a complete electronics system that must be protected. The whole system is usually mounted on shock absorbers that reduce the local stress on the display components. Nevertheless, most consumer-grade displays must be ruggedized to prevent mechanical damage. External temperature variations are moderated by the presence of the ocean. However, the operation of the display and other equipment can generate significant amounts of heat so that air cooling must often be provided. Ambient light conditions are usually controlled except for displays on small boats and on the bridges of large ships.

The Q-70 program is an effort to standardize electronic components, make use of ruggedized consumer products, and encourage open system connections in mission-critical systems. Equipment for less critical situations is coordinated through the TAC-4 program.

3.4.4 SOLDIER-PORTABLE DISPLAYS

Microelectronics is bringing the full range of battlefield information to individual soldiers in action and is providing the field engineer with access to maintenance data without having to carry multiple manuals. This information can be viewed using a head-mounted display (HMD), the screen of a hand-held personal data assistant (PDA), or a personal computer. Our attention will be concentrated on the third category: There is as yet no well-established commercial market for HMDs, and the PDA market is too volatile for long-term planning. Military combat applications of HMDs have performance requirements that exceed those of commercial users.

The Lightweight Computer Unit (LCU) is a good example of common hardware that uses ruggedized consumer equipment. Over 13,000 liquid crystal displays have been fielded through this program. The current unit, V2A2LC, uses Pentium processors and 9.4-inch and 10.4-inch AMLCDs. The unit is ruggedized to a modest extent. The operating temperature range is only -25 ^{o} C to +49 ^{o} C, and the “drop” test is only from two feet. The unit is tested for resistance to a wide variety of hazards, including sand, dust, rain, vibration, fungus, and water immersion. The protection that is necessary to provide just this environmental protection raises the weight of the unit with standard accessories to over 30 pounds.

3.4.5 COMMAND AND CONTROL SYSTEMS

Command and control applications require rugged, high-resolution workstation-sized FPDs and portable large area displays (21-inch and larger diagonal measurement). Portable FPD-based systems provide a lightweight, thin profile, lower power consumption solution to viewing information related to battle operations such as maneuver, weapons targeting, combat analysis, and command and control planning and management. The ability to conduct mission planning and analysis using digital map information drives Service interest in employing large area FPDs.

3.5 SUMMARY OF REQUIREMENTS

Table 2 depicts the challenges created by environmental stresses for various military applications. The numbers in the table indicate judgments regarding the relative difficulties of meeting each requirement:[16]

> "0" indicates that the requirement can be met by an unmodified consumer display.
>
> "1"indicates an upgrade in durability or performance is needed, which can be attained using ruggedized consumer displays.
>
> "2"indicates the need for major modifications in order to use a ruggedized consumer display or the use of a custom FPD.
>
> "3" indicates a very high level of stress or performance that can normally be met only by custom displays.

[16] These are estimates of the study team. They are generalizations for the particular category and there may be specific programs where a score might be higher or lower.

Table 2: Relative Severity of Typical Environmental Requirements

Category	Examples	Form / Fit	Temp Range	Light Levels	Shock / Vib.	Foreign Matter
Combat Aircraft	F-16, F-18, AH-64	3	3	3	2	1
Support Aircraft	C-130, E-3, P-3	1	2	0	1	1
Combat Vehicles	Abrams, Bradley	2	3	2	3	2
Support Vehicles	Crusader resupply	1	1	1	1	2
Shipboard	Q-70 TAC.4	0	1	0	1	1
Soldier Portable	LCU, manpack radio	0	1	1	1	2

This table shows that ruggedized consumer-grade FPDs can meet the environmental requirements for a broad range of military applications. It also shows that there is one application area, combat aircraft, that requires the use of custom FPDs for three categories: light levels, temperature range, and form factor. In addition, custom FPDs are also needed to provide multifunction capabilities to display sensor data.

4. MEETING REQUIREMENTS: ACQUISITION PRACTICES AND THE INSERTION OF FPDS

4.1 INITIAL APPROACH TO FPD ACQUISITION

DoD began to acquire FPDs for military applications, using a traditional acquisition approach in which DoD sought to develop on its own capabilities for meeting defense-specific needs. Many early applications were for combat systems that operated in harsh and extreme environments. At that time (late 1980s to early 1990s), FPDs were becoming popular in laptop computers, but their performance was substantially less than what the military applications required.

DoD viewed FPDS as an emerging technology that would play a major role in expanding the information capabilities available to the warfighter. As a result, DoD funded considerable R&D in advanced displays, particularly through DARPA's High Definition Systems Program. The organizations conducting this work in advanced FPD technology were for the most part, R&D organizations, not FPD producers. The United States had little production capabilities in FPDs and the FPD business was almost entirely in Japan.

In the 1994 assessment of U.S. capability[17] in FPDs, concerns were raised that DoD R&D was not leading to FPD production capabilities and that the insertion of FPDs into military systems was encountering obstacles. This led to the National Flat Panel Display Initiative (NFPDI).

The NFPDI explicitly supported interests in the military services to acquire and insert FPDs into military systems, most specifically aviation cockpits. The Title III program of the Defense Production Act (DPA) explicitly supported insertion of AMLCD displays

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[17] *Building U.S. Capabilities in Flat Panel Displays,* Department of Defense, October 1994.

in aircraft cockpits of the Apache, F-16, P-3, F-18, AV-8B, CH-46, C-141, and UH-60Q, as well as the Driver Vision Enhancement (DVE) program. Under the Title III program, DoD provided $27 million in incentives to insert AMLCD FPDs in cockpits. These financial incentives were made available to military program managers to fund the testing and qualification of FPDs for insertion into specific military cockpits. Title III funds also helped to expedite the establishment of a domestic AMLCD industrial base by funding the early production of displays for later planned insertions in specific weapon systems. Because the DPA, Title III by law exclusively focuses on a domestic industrial base, only U.S. and Canadian FPD makers could participate.

4.2 PROBLEMS IN THE INSERTION OF FPDS INTO MILITARY SYSTEMS

The process of acquiring FPDs and inserting them into defense systems has not been a smooth one. There has been a rocky transition from an R&D mode to a production and acquisition mode. The technology itself was maturing, but the experience in applying it to such demanding systems was very limited, and the production base for advanced FPDs was minimal. In retrospect many of the program managers overseeing the insertion of FPDs have concluded that the difficulties of bringing this technology into production and implementation for defense systems were significantly underestimated.[18] The resources needed to ramp up production and incorporate the technology were greater than anticipated, either by the display glass producers or the display system integrators.

The requirements that were targeted by DoD programs inserting FPDs were well beyond existing state of the art, so that these efforts required significant development work. Moreover, the scaling up of these developments into production required bringing on-line new facilities implementing new processes, adding to the risk. Aggressive insertions placed time and cost pressures onto firms that were essentially R&D organizations and thus not accustomed to the strictures of production and the premium placed on delivering to schedule.

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[18] This was not uniquely related to FPD technology. Other examples of problems of transitioning an emerging electronics technology into application and production include Monolithic Microwave Integrated Circuits (MMICs) and focal plane arrays.

DoD's manufacturing test-bed programs helped to defray some of these risks. Even so, the custom FPD firms encountered major problems in ramping up production operations. To overcome these problems, display integrators and prime contractors expended considerable efforts of their own to help the display producers, even to the point of sending display integrator or prime engineering staff to the production facilities.[19]

This set of experiences led program managers and their prime and sub-tier contractors to look for alternative paths for meeting their display needs. One option pursued has been the establishment of second sources. But this has been difficult because the existing custom producers were already having difficulties meeting their existing orders, and were not in a position to bail each other out. Moreover, new sources that were coming on line had difficulty demonstrating that they could avoid the production ramp up problems that the other custom producers had already experienced. In addition, it takes money to cover the non-recurring engineering costs needed to bring another firm into production. The non-recurring expenses for engineering a military avionics display for another application and the required production process have been put at about $1 million.[20] However, the program offices and prime contractors had already expended their available Non-Recurring Engineering (NRE) on the initial display producers (and often considerably more than originally intended). Consequently, the integrators and primes were not eager to pay additional money to another unproven vendor.

These problems in obtaining custom FPDs made more attractive the prospect of getting consumer-grade display glass from commercial sources and then "ruggedizing" these displays to meet harsher or more stringent performance needs. Ruggedized consumer-

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[19] It should be noted that not only did the glass producers encounter difficulties, but so did the integrators as well. For the F-22, there have been problems with display integration, backlight performance, driver electronics, as well as with the delivery of the AMLCD glass.

[20] This is based on interviews with custom FPD producers and military display system integrators. Moreover, these difficulties were not solely due to the military nature of activity. Boeing encountered considerable difficulties in getting FPDs developed and integrated into 777 cockpit; see Appendix B.

grade FPDs were being used already in some military programs, including embedded combat systems, but not for the most stressful requirements such as fighter and combat helicopter cockpit displays. The delivery problems with custom FPDs for these applications opened up the prospect of using commercial displays.

4.3 AFFORDABILITY AND DISPLAY INSERTION

Another important factor that affected FPD acquisition decisions was the increased focus on affordability, given the decreasing DoD budget. DoD has made major efforts to revamp its acquisition process with the aim of acquiring defense systems more affordably, with a major emphasis on the use of commercial components to meet defense needs wherever possible. Many of DoD's Acquisition Reform programs were being implemented about the same time as DoD's effort to insert FPDs into defense systems.

A fundamental driver of the increased use of commercial displays in defense systems is reduced budgets. As one program manager put it, "We're using COTs because there is no money." The emphasis on affordability in DoD has had major impact on how program managers and system integrators make decisions, and raises new risks regarding the use of commercial components, such as consumer-grade FPDs. These risks include insufficient knowledge of the downstream impact of commercial displays regarding:

- their ability over the life of a system to meet required environmental and performance capabilities; and
- their continued availability (or the availability of reasonable alternatives) over the life cycle of the system.

Concerning the first issue, Service program office personnel have expressed concerns that displays used in aircraft cockpits are "safety critical" and mission-critical primary flight instruments. For such items it would be imprudent to use capabilities that are not well tested and understood. The Services are responsible for assuring that any displays used in the cockpit function at the required levels of performance and would be reliable and capable over their intended service life. This raises questions regarding the type of capabilities and investments that are needed to provide this assurance.

- What knowledge is needed to determine whether custom FPDs are necessary to attain the required military performance, or whether ruggedized consumer-grade FPDs are capable of providing it?

- Who is responsible for conducting the assessments and at what stage of the acquisition process should they be conducted?

- Are contractor qualification tests sufficient or are independent assessments by Service organizations needed?

From interviews with Services personnel, it is apparent that currently there is lack of clarity on what the Service role in this area should be. The issue of testing display performance is further discussed in the next chapter.

The issue of longer-term availability focuses on the rapid product turnaround of commercial display producers. The concern raised is that a consumer-grade display designed into a military application will become obsolete relatively early in the weapons application life cycle. By the time a commercial display product is ruggedized and integrated into a weapon system, it may no longer be available. This product obsolescence could cause redesign and re-qualification, the costs of which could be millions of dollars in NRE. *The concern is that while consumer-grade FPDs are favored because they offer prospects of substantially reduced initial procurement costs, their use may result in future costs that are not factored into acquisition decisions.* Some display integrators interviewed contended that if life cycle replacement and upgrade costs were included in a program's financial decision, custom FPD products would be more affordable over the life cycle than using ruggedized consumer-grade FPDs.[21] Chapter 6 on life cycle cost presents a fuller discussion of this issue.

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21 The Crusader program is one example, with TACOM buying 3,000 displays over 8 years. If custom displays cost as much as $3,000 more than ruggedized COTs FPDs, the custom FPD acquisition would cost an additional $9 million. However, in a full life cycle cost assessment, this cost would need to be compared with two redesign cycles due to obsolescence of the commercial glass, or the costs of lifetime purchases of the "obsolete commercial glass." On the other hand, custom FPDs, produced by a single source could become increasingly costly, particularly as DoD demand decreases after the initial procurement is completed.

On the other hand, military-specific products have obsolescence problems as well. One concern is that military-specific vendors may leave the market if the volumes and prices are insufficient to sustain a viable business. The problem of "diminishing" defense manufacturing sources is already a problem for DoD in military-specific electronics. Highly specialized custom FPD firms are competing for a small volume of business stretched over many years at a time when there is severe pressure on product cost and a premium on delivery to schedule. Several custom firms have recently exited this market, raising concerns over the stability of the remaining custom firms.

4.4 "CUSTOM" VS. "RUGGEDIZED" FPDS

Military display system integration is a custom process. Most military displays are ruggedized and integrated into a larger military display system. Main areas of concern in ruggedizing an AMLCD are:

1) Components and connectors;
2) Liquid crystal temperature range;
3) Bonding of the drive electronics;
4) The laminations for the polarizers and the backlight; and
5) Packaging to address shock, vibration, and other environmental concerns, such as electro-magnetic interference (EMI).

The display is only one element of a complex electronics system that integrates a variety of inputs, processes them, and provides outputs. Many of these elements differ in important aspects from those used in commercial applications. Prime contractors usually subcontract to sub-system vendors to provide an integrated electronics capability, and these vendors usually contract out the display system development.

Display system development usually involves several "customizing" steps often involving different vendors. Most display integrators acquire the FPD itself and then build up the display systems, using specialized sources for "ruggedizing" and "enhancing," Optics engineering for military flat panel displays is highly specialized. Expertise in this area was initially limited but over time has grown. Some firms have specialized in providing optics solutions to integrators, but now optics specialists have moved further up the value chain while many integrators have developed their own optics expertise. The degree of specialization in the FPD supply chain has decreased: Firms are positioning themselves for greater value-added, and seek to eliminate reliance on outside specialists, some of whom are now competing in the display system integration business.

Sources of customized display glass are limited, as most consumer display producers are not interested in disrupting their production. During downturns or periods of overcapacity, commercial display glass makers may be more interested in meeting special needs than during periods of high demand for commodity products. There appears to be a growing interest among some larger-scale commercial FPD producers in business beyond or instead of the commodity laptop computer market. In the future, these suppliers may be more interested in providing customized FPDs for meeting DoD's specialized needs.

4.5 ACQUISITION PRACTICES FOR MILITARY FPDS

It is generally acknowledged that the industry did not realize how difficult and costly it would be to deliver FPDs that met original military specifications. As the F-22 program started to develop AMLCD FPDs, it had only two possible sources of custom display glass available, Sextant of France and OIS, a U.S. firm.[22] At the time, consumer-grade AMLCD makers were not interested in supporting the low-volume, highly specialized military display market. OIS won the competition over Sextant, but it had not previously delivered production displays. It faced daunting problems in ramping up production for the F-22. While that display was under development, OIS also took on a number of other projects such as the Apache and F-16. OIS was not alone in facing such production ramp-up problems. Two other custom AMLCD vendors, Image Quest and Litton of Canada, had difficulties in moving their AMLCD technology into production. Both these firms were unable to make deliveries to military programs—such as the C130-J and the Bradley Fighting Vehicle for Litton, and the P-3 for Image Quest—and were replaced by other vendors. Litton and Image Quest recently withdrew from the custom FPD market.

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22 Sextant, a subsidiary of the French firm Thomson, acquired the military FPD technology of RCA when Thomson acquired RCA.

Over the past decade the military program offices and prime contractors have been increasingly unwilling to accept any increases in price or schedule delays. As a result, the "requirements" stated in acquisition actions have been relaxed sometimes. But both custom display makers and display system integrators have voiced concerns that it is unclear exactly what is in the "trade space" and what the real programmatic priorities are. This leaves custom display makers and integrators concerned about whether performance improvement is appropriately considered in program decisions. From their standpoint, the cost-performance tradeoff appears to be focused almost exclusively on near-term acquisition cost. (Chapter 6 on life cycle cost discusses this issue further.)

4.6 SUPPLY APPROACHES

The current supply channels for military FPD applications can be grouped into three modes:

1) Custom manufacture on low-volume, specialized fabrication lines;

2) Custom manufacture on high-volume lines ("semi-custom"); and

3) Ruggedization or re-manufacture of consumer-grade FPDs.

The merits and risks of the three approaches for meeting military needs are discussed in the following sections.

4.6.1 CUSTOM MANUFACTURERS FROM LOW VOLUME SUPPLIERS

Several domestic firms have been involved in the development and production of custom displays for use in military applications. Initially, there were major problems in transitioning from R&D activities to production as firms learned the intricacies of display fabrication, including the setting up of manufacturing equipment and accessing supplies of materials. Today U.S. companies such as Planar, OIS, and dpiX have demonstrated that they can produce state-of-the-art products for military applications. Prices for such displays are somewhat higher than of those of ruggedized COTS displays, but their performance is optimized for military use. These custom FPD producers have expressed a strong commitment to meet DoD's needs, but their short and unproven business history has led to concerns over their economic sustainability.

The manufacturing flexibility of small-scale producers means that they can provide a variety of FPDs in smaller batches. From the standpoint of an individual military program, the ability to fill small-batch orders allows modifications to be made in the transitions from engineering development to limited production and then full production. However, the set-up cost for unique displays can lead to substantial unit costs for very small orders.

The major uncertainty in pursuing the custom FPD approach lies in the financial health of these suppliers. The three companies cited above have different records in this respect. Planar is one of the very few companies in the global FPD business that has been consistently profitable. This is because its primary technology, ELDs, has evolved relatively gradually (in comparison to AMLCD), and because military displays have been only part of a broad business strategy. OIS has concentrated most of its resources upon the development of high-reliability AMLCDs for the advanced avionics market, primarily for defense applications. In building its production capabilities and ramping up production, OIS has sustained substantial losses, amounting to approximately $30 million in 1997.[23] It has targeted medical sensors as its primary commercial focus, but is now just entering this business. dpiX is a newly formed company, having spun off as a subsidiary of Xerox last year, and thus has only a limited production record. It has developed some advanced AMLCDs for civilian applications that are synergistic with its military products. dpiX is pursuing a dual-use strategy, but its ultra-high performance displays are suitable mostly for niche applications, the commercial viability of which is not yet clear.

While a steady flow of military orders is crucial to the success of these companies, relying solely on the small volume of very demanding defense applications does not appear to be a viable option for the DoD domestic custom suppliers.

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23 Optical Imaging Systems, announcement of FY 1997 financial results as reported by PR Newswire, September 29, 1997.

4.6.2 CUSTOM FPDS FROM HIGH-VOLUME SUPPLIERS

High-volume FPD producers generally are not interested in developing display products for specific niche markets such as the military. However, electronics integrators such as Honeywell and Rockwell-Collins, which are involved in both defense and civilian aviation markets, have been able to establish development and production relationships with high-volume FPD manufacturers. Because these FPDs must be designed to conform to the existing high-volume production processes, this approach is sometimes referred to as “semi-custom.”

The best established semi-custom relationship today is between Sharp and Rockwell-Collins. This arrangement is based on a 30-year corporate relationship that transcends FPDs. Sharp builds FPDs to Rockwell’s specifications, which Rockwell has already matched to Sharp’s manufacturing process. Several thousand of these semi-custom FPDs have been inserted into aviation systems, both commercial and military. Sharp shares proprietary FPD design rules with Rockwell-Collins, and Rockwell-Collins shares laboratory findings on improvements to Sharp’s AMLCD technology. Sharp has assured long-term availability to Rockwell on all current products.

A primary advantage of this approach is the timely access it affords to the best technology from the consumer world. However, it is unclear whether the supply relationships being developed by other display integrators will achieve this level of technology sharing, cooperative planning, and supply assurance. Furthermore, the success of the Rockwell-Sharp relationship is based on factors that might be difficult for other defense applications to achieve. The two main limitations are:

- The approach requires a prospect of substantial sales. Developing such supply relationships requires considerable investment of time and resources. A representative of a major electronics integrator has estimated that his company has invested about $50 million to date to establish and maintain its partnership. A minimum production run of at least several thousand FPDs is required to make the arrangement attractive to a high-volume producer and affordable for the customer.

- The current and proposed semi-custom supply arrangements are exclusively in dual-use avionics. These FPDs are predominantly used in commercial aircraft. Other DoD applications might not be able to take advantage of such military-commercial overlap. It was only three years ago that DoD invested in domestic custom FPD suppliers because of a stated unwillingness of foreign FPD producers to work with defense integrators. Japanese laws explicitly prohibit directly supplying the U.S. military.

The "semi-custom" approach to acquiring FPDs for military applications is relatively new and unproven. Although foreign suppliers have promised long-term support, the supply of FPDs through such an approach cannot be regarded as completely assured. The difficulties of Hosiden, a major supplier of displays to Honeywell for use in the Boeing 777, shows that major Japanese companies are not immune to financial crises. Hyundai, a Korean conglomerate, recently withdrew its support for Image Quest.

4.6.3 RUGGEDIZATION OF COMMERCIAL DISPLAYS

Most ruggedized displays use unmodified LC cells. The civilian display market is expanding into outdoor and transportation applications, and commercially available AMLCDs are becoming more easily adaptable to military applications. The major concern regarding the availability of commercial displays comes from "upgrades" intended for the civilian market. These upgrades can result in changes in size, resolution or electronic interfaces as much as every two or three years and can lead to significant problems in obtaining additional or replacement units. Lifetime buys provide a possible solution, but the expense of procurement and storage must be met. There is also a risk the program maybe canceled or reduced, making a lifetime buy a wasted expense.

Some ruggedized AMLCD displays are based on LC cells that are slightly modified from those available in products for the civilian market. For example, FPDs that were intended for use in landscape mode can be produced for use in portrait mode with relatively minor changes on the fabrication line. In times of excess capacity, manufacturers may be willing to dedicate a day, or perhaps even one shift, for modifications that do not require retooling or reconfiguration in the fabrication line. This may enable the acquisition of batches of a few thousand displays or more.

Apart from the source of the FPD glass, the financial health and commitment of the ruggedizer are also a matter of concern. This type of work has been performed both by small divisions of large defense contractors and small entrepreneurial companies. The realignment of the defense industry has led to many sales or divestitures of subsidiaries. So far, most of the "spun-off" units involved in display ruggedization have been bought by other companies or by their employees. Nevertheless, the fluidity of the situation warrants attention, both with respect to maintenance issues and supply reliability.

4.7 SUMMARY OF ACQUISITION ISSUES

The design of a display system involves hundreds of technical choices, each of which can affect numerous display characteristics. Decisions at every layer of a display system can affect performance as can the design of supporting electronics and software. For instance, achieving a certain color saturation for a particular shade of red in an AMLCD will depend simultaneously on the output spectrum of the backlight, the cell gap and color filters within the LC cell, the properties of the various lamination layers as well as other design choices. Changing the design of one item to improve certain optical performance will typically diminish other performance.

Given the degrees of freedom in FPD system design, there are numerous tradeoffs involved in attempting to achieve the environmental and performance characteristics desired for military applications. In assessing the decision to use consumer-grade vs. custom FPDs, it is important to distinguish design choices among:

1) The system level, available to the systems integrator, installer, or user of a finished display system;

2) The LRU and display head levels, available to the display system integrator (e.g., a ruggedizer of consumer displays); and

3) The LC cell level, available only to a custom LCD fabricator.[24]

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[24] While this discussion focuses on AMLCD displays, simila arguments could be made for an alternative technology.

In practice, most system-level design choices are not adjustable by a display system integrator. A space budget, environmental conditions, and required performance characteristics are flowed down by the prime contractor and generally are not open to negotiation. If the display system integrator is providing a display head to an LRU manufacturer, the design freedom of the display integrator will be limited to the four major display head subassemblies: the LC cell, laminations, driver assembly, and backlight assembly.[25] A display system integrator who uses consumer-grade AMLCDs cannot control technical choices within the LC cell and hence is limited to design choices in other subassemblies.

In cases where system and LRU-level decisions are fixed, the military environmental and performance characteristics that prelude using consumer-grade FPD glass are specific sizes to fit existing holes, extreme temperatures, and extreme brightness. Other characteristics can be met using consumer-grade FPDs, with differing degrees of difficulty and cost, depending on the performance level desired. In actual practice, as discussed above, certain military specifications have proven difficult to meet even using custom FPDs. Due to lack of experience with the technology, these initial specifications were set high and then modified to meet what could actually be accomplished. Specialized AMLCD producers had major difficulties delivering products on schedule that met these initial performance specifications. These delivery problems appear to be resolved for current programs, but some program offices and prime contractors have expressed concerns that the production base for custom FPDs is still not sufficiently robust to assure future deliveries.

25 See Chapter 2 for a detailed discussion of AMLCD display head design.

5. TESTING FPDS FOR MILITARY APPLICATIONS

Two approaches to evaluating FPDs are (1) the testing of displays against the requirements set in a development or procurement contract, and (2) the comparative testing of FPDs to set requirements for a particular military application. The first approach is part of the process of assessing how well an FPD integrator has met a set of already specified requirements, or the qualification of the FPD against a set of requirements. The second approach is focused on developing the requirements themselves or on characterizing the capabilities of alternative types or sources of FPDs for a particular military application.

5.1 TESTING DISPLAY PERFORMANCE AGAINST CONTRACTED REQUIREMENTS

FPDs are qualified by individual vendors against contracted environmental and performance requirements. This process has generated extensive military program-specific test data on selected consumer-grade and custom FPDs. However, such test data are generally viewed as proprietary by the FPD integrator and the prime contractor, and hence are not made available across programs or to other contractors. Usually such performance data are collected only for assessing the degree to which a particular display system meets specified requirements.

As discussed previously in Chapter 4, military programs have aggressively inserted FPDs, including development efforts that pushed the state of the technology. These are frequently "build-test-modify" efforts in which the display integrator works with an FPD producer in building a prototype display system to meet specified requirements. This display is then tested to determine whether the performance has been attained. [26]

[26] Examples of this development and test process are given in Appendix B for the F-22 for a custom FPD and the C-130H for a ruggedized commercial FPD. Also Boeing used a similar development process for the insertion of FPDs into the commercial 777 cockpit. This is also discussed in Appendix B.

If the tests show the display system to be deficient, the contracting parties will usually continue to explore ways to improve performance until the requirement objectives are satisfied.

However, cost and schedule constraints restrict this development process. Rather than pursuing additional efforts to meet a particular performance specification, the integrating contractor can:

- Waive some elements of the specified requirements, and accept the development effort as being "good enough," either temporarily or permanently.
- Cease the effort and contract with an alternative supplier to develop the specified product.
- Cease the development effort and contract with another developer to provide another display solution, with perhaps relaxed requirements.

Concerns have been raised that decisions to grant waivers on specified requirements have been made without sufficient study of the mission consequences. This concern deals with a type of assessment different from that which is normally performed in qualifying an FPD for use in a system, or in evaluating whether a particular FPD meets specified requirements. This calls for an assessment of the mission effectiveness of the system, given that it did not meet specified requirements (compared to mission performance if the requirements could be met). Such analyses can be conceptualized and perhaps could be approached through modeling and simulation, or through a comparative prototype development and evaluation. However, these would be costly and time consuming activities.

In conducting this study, the IDA study team found examples of decisions to accept a display system that did not meet the initially specified requirement. These decisions generally were strongly motivated by schedule problems in the delivery of custom FPDs—which, in turn, imperiled the weapon schedule itself. When a program reaches such a state, performing an extensive, time-consuming, and costly assessment would be difficult and would conflict with the need to make a timely decision. While the contractors and the program office clearly have to acquire and use as much data as they can reasonably gather to make an informed judgment on whether to accept a lesser capability for the FPD system, these cost and time constraints must be appreciated. Programs must be concerned that missions not be jeopardized, but they also need to be allowed to perform reasonable performance, cost, and schedule tradeoff decisions, particularly when a supplier is unable to deliver the specified product.

One means to improve the ability to make such decisions, and to better set requirements at the beginning of a program, is better comparative data on display performance for specific military applications. While some programs have adopted lessons learned from others, this has been done only on a limited and *ad hoc* basis. With little availability of shared data on FPD system performance, programs have reached different judgments about the environmental tolerance and optical performance of ruggedized consumer-grade FPDs. Lacking credible characterization of FPD performance, some programs have been reluctant to use consumer-grade FPDs. The topic of comparative assessments of FPDs is discussed in the next section.

5.2 COMPARATIVE ASSESSMENTS OF FPD CAPABILITIES

While comparative assessments of FPD performance for particular military applications would be useful in both requirements setting and subsequent decisions regarding FPD acquisition, this study identified only a few such comparative assessments. A recent study of FPDs for transport aviation showed wide variation in the level and quality of ruggedization, and that some ruggedized consumer-grade FPDs, as well as already available custom FPDs, can meet the performance requirement of transport aviation.[27] This study highlights an important point that ruggedized FPDs developed for one application will not necessarily meet the needs of another.

For combat aviation, Battelle inserted a prototype display system using a ruggedized, COTS FPD into an F-16 cockpit on an experimental basis.[28] It was determined that this FPD could meet many of the combat aviation requirements, but it was deficient in resolution and was a different size than the CRT it would replace. The FPD had to be

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27 Unpublished study conducted by Boeing for Battelle, under contract to Wright-Patterson AFB.

28 Randall E. Orkis, "An Improved Full Color F-16A/B and F-16C/D Multi-Function Display Using a Ruggedized COTS Active Matrix Color Liquid Crystal Display," Columbus, Ohio: Battelle Memorial Institute, circa 1994.

ruggedized to meet military environmental requirements. However, the COTS-based system was designed for full color video, which is a highly desired capability that was not available in custom FPDs (at the time). This test development effort demonstrated the trade-offs between a custom and a ruggedized COTS FPD, and showed the potential for using ruggedized consumer-grade FPDs in combat aviation if programs were willing to accept specific limitations.

Honeywell recently completed a project assessing the use of automotive-grade AMLCDs in the F-16, with specific emphasis on thermal management and an driver-dip bonding.[29] This program concluded that "some specific design amendments … permit the use of commercial (automotive) industrial-grade displays even in challenging F-16 cockpit conditions." However, there were some important caveats:

1) For displays with active areas larger than 5x5 inches, cooling air or some measures to reduce solar load are needed;

2) The cost of ruggedized and enhancing the automotive-grade display to meet the F-16 requirements brings its cost close to those of custom FPD systems.

In another assessment, Battelle has examined a wide range of available technologies to meet the Common Large Area Display Set (CLADS) specification intended to capitalize on available consumer-grade displays.[30] Battelle has performed test and evaluation on a variety of display technologies. These include AMLCD, plasma, and digital mirror projection. Based on analyses to date, critical performance criteria have been met or exceeded by one or more of the technologies tested by Battelle. Detailed performance criteria for this effort are shown in Appendix G.

The number and scope of comparative assessments of FPDs in military applications are not great. Moreover, there are few resources available for such assessments. Attention

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29 James B. Armstrong, Sonia R. Dodd, and James M. Henz. "Display Ruggedization for Military Applications Using Automotive-Grade Active Matrix Liquid Crystal Displays." Draft Report, Phoenix, AZ: Honeywell, Inc., December 1997.

30 Ronald L. Gorenflo and David J. Hermann, "21 Inch Technology Independent Common Display Set (CLADS) Design for Rugged Workstation Applications," Columbus, Ohio: Battelle Memorial Laboratories, 1997.

needs to be given to greater sharing of data and to encourage cooperative efforts in conducting comparative assessments of FPD performance.

6. FPD LIFE CYCLE COST ISSUES

This chapter explores the life cycle cost (LCC) of FPD technology as it impacts display systems, military platforms, and the accomplishment of defense missions. It also discusses how programs consider LCC in FPD system acquisition. The findings cover both the explicit and implicit questions in the Congressional request:

- What are the life cycle cost implications in using custom vs. consumer-grade FPDs in military display systems?
- Are appropriate methods and data available to assess life cycle costs?
- Are programs taking an excessively short-term approach in evaluating costs, thereby neglecting life cycle considerations?

Chapter 7 picks up on the findings presented here to address the strategic, cross-cutting issues associated with LCC: open systems, commonality, and availability of FPDs.

6.1 LCC AND FPDS

DoD pioneered the concept of LCC in the 1960s. Recently, LCC has been given increased attention in system acquisition. This section describes the LCC concept and lays out some of the issues in making LCC assessments in the FPD domain.

LCC is the combined cost of acquisition and ownership. Acquisition costs for an in-house effort include conceptual design, detailed design / development, and production. When a system is purchased, the acquisition cost would be the purchase price plus inspections, testing, and overhead (invoicing, material handling, etc.) Ownership costs include various operations and support (O&S) activities—facilities, training, replacement spares, etc.—and retirement / disposal costs.

LCC can be considered at levels other than the system level. A system is typically embedded in a platform that is used to accomplish a mission. Increasing the LCC measured at the system level could reduce LCC measured at the platform and mission levels. For example, FPD systems often display sensor data for aircraft, ships, and armored vehicles. A more costly FPD system capable of handling high information rates might permit one system operator to do the same work currently performed by two. Reasoning further, a more capable FPD system might improve mission performance to the point where fewer aircraft, ships, or armored vehicles are required. Maintaining fewer platforms reduces the number of support personnel, fuel, and facilities required.

In this way, improvements in individual systems can have amplified effects on LCC at the mission level. Costly changes in system performance may be cheap at the mission level. Hence, it is important to consider platform and mission effectiveness in order to make sound LCC decisions at the system level. The complex connection between system capabilities and mission performance can make precise assessment an onerous burden. The implications of FPD technology for an avionics application will be different from those for a ship or an armored vehicle. The fact that FPDs are a relatively new and immature technology increases the difficulty of anticipating their implications for mission LCC.

This being said, it is still possible to make some general statements about the LCC implications of FPD technology. FPD-based systems are lighter and more reliable, consume less power, and take up less space than CRT-based systems. These qualities reduce ownership costs in a variety of platforms and missions. Reliability is particularly important. FPD systems, whether custom or ruggedized consumer-grade, are typically ten to twenty times more reliable than the CRT systems they replace.[31] The "mean time between failure," (MTBF) for many CRT systems is measured in hundreds of hours; in comparison, MTBF is measured in thousands of hours for comparable FPD systems. For instance, the MTBF for the CRT system in AWACs aircraft is approximately 300 hours while the MTBF of the FPD system being supplied to the

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31 This study did not uncover data that indicated any reliability advantage in using custom vs. consumer-grade FPDs except in high-temperature environments. In practice, consumer-grade FPDs are designed and specified to operate in a limited temperature range, and higher temperature environments require operation outside this specified range. Exposing FPDs (or any other piece of equipment) to temperatures beyond their specified range will likely lead to early failures (and result in reliability problems).

Apache helicopter is estimated at more than 5,000 hours. The MTBF for the FPD system in the Bradley armored personnel carrier is estimated at 7,000 hours. FPD systems in the C-130H and C-130J have accumulated more than 700,000 hours in the field with only a handful of failures (after an initial problem was solved).

Low failure rates reduce the cost of maintenance in terms of personnel, spares, training, and the like. Most FPD system integrators serve as repair depots for the equipment they manufacture, with turnaround times as low as twenty-four hours. Fast repair time saves resources at the platform and mission level by improving readiness. The costs of having a weapons platform grounded quickly adds up and the reduced failure rates of FPDs greatly impacts the costs.

FPD technology also reduces platform and mission ownership costs in less obvious ways. In avionics applications, size reduction helps designers optimize cockpit structure to reduce overall drag. FPD flexibility permits the user interface of a new avionics suite to mimic the appearance of legacy systems, reducing pilot-training costs. Miniature, head-mounted FPD systems improve war fighters' target recognition and weapons operation.

The reduction in LCC from using FPDs can be offset by higher acquisition and replacement costs. Initial development, production, qualification, and integration efforts, particularly for custom FPDs, have been complicated and risky. Early defense efforts spent tens of millions of dollars on development of specific designs in addition to earlier DoD R&D and production technology investments.[32] These NRE costs are amortized over a relatively small number of display systems.

For consumer-grade FPDs, replacement cost is a major concern. Some display integrators believe that over a weapons life cycle, consumer-grade FPDs could be more expensive than custom FPDs due to rapid commercial product obsolescence. For example, although the use of a ruggedized 10.4" diagonal 4x3 aspects ratio display was

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32 In many cases, NRE costs (principally qualification costs) were paid in part out of funds provided by Title III of the Defense Production Act. A total of over $25 million of Title III funds has been used for this purpose. A program using Title III funds is required to employ a domestic source for FPDs, which means a custom FPD. Approximately $30 million in Title III funds provided the initial production equipment for a team of AT&T, Standish as Xerox (now dpiX).

planned for the Comanche helicopter (RAH-66), the anticipated LCD supplier discontinued the product in favor of a 12.1” screen just as the first demonstrator aircraft was being tested. Today, replacing the FPD in an existing system costs about one to three million dollars in development effort. The cost could be much higher if replacement FPDs are not readily available.[33]

Generally, the high MTBF of FPD systems should make the need for replacement rare, but a program may still need to replace several hundred or even a few thousand displays over its life cycle. In assessing the LCC implications of these replacements, the cost entailed in using commercial FPDs must be balanced against the higher development and procurement costs of custom FPDs. As an example, if a $3 million engineering effort were needed to replace a discontinued consumer-grade FPD by another, these costs would be comparable to those of procuring a thousand custom FPDs that each cost $3,000 more than the ruggedized consumer-grade FPD. However, the cost of replacing a custom FPD, should it become unavailable due to its supplier exiting the business, or shifting to other products, would be at least as costly. Thus supplier stability is an important factor in life cycle assessment, but an extremely difficult one to predict for such a new and changing industry.

The combined FPD LCC effects of improved mission performance, higher reliability, higher acquisition cost, and availability risk cannot be established precisely. They vary by application, and the relative importance of these factors can be expected to change due to evolving FPD product and manufacturing technology, changing industry structure, and lessons learned about inserting FPD into defense applications. The following subsection describes how individual programs addressed these issues.

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33 Display integrators using consumer-grade FPDs state that older FPD products have continued to be available for extended periods. When a commercial product has been withdrawn from the market, the supplier either made suitable alternatives available or provided sufficient notice for lifetime buys to be arranged.

6.2 CUSTOM VS. CONSUMER-GRADE FPDS

Programs are motivated to insert FPDs in order to reduce platform and mission LCC. Reliability and availability problems with CRTs are a primary motivation for programs to consider FPD insertion. The fact that FPDs can fit in narrow spaces is motivating their use in applications in which installation of a display system was previously impractical. However, this study found few formal evaluations that tie specific FPD system performance characteristics to platform or mission LCC. Likewise, this study found few programs where the LCC of a proposed FPD system was a primary selection criterion. The CLADS program, now in the process of issuing a solicitation, does have LCC as a primary criterion. Generally, programmatic decisions selecting between custom and consumer-grade FPDs have not been based primarily on LCC.[34]

Participants contacted by this study suggested that the highly competitive environment in which most programs currently find themselves encourages concrete, immediate savings over uncertain, future life cycle savings. LCC estimates are often shaped by political prerogatives. Making the total ownership costs of a system visible at the outset can make the system seem “too expensive” and lead to its cancellation. The study team heard many anecdotes about programs that changed their specifications after the contracts were awarded and contractors who promised to meet performance goals while looking for weaknesses in the Request for Proposal that could be “corrected” later with expensive Engineering Change Proposals.

In most cases, consideration of LCC was dominated by concerns about delivery. Many programs were faced with the prospect of platform delivery delays due to a late delivery FPD system. Display integrators and primes contacted by this study reported losing “tens of millions of dollars” due to FPD delivery problems. In some cases, this schedule pressure drove the decision to employ a ruggedized consumer-grade FPD rather than a custom FPD.

Programs not facing immediate delivery problems were typically concerned more with initial acquisition cost than with LCC. Custom AMLCDs have higher acquisition costs

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[34] As discussed in Appendix B, LCC was a major factor in the Abrams display program.

due to special design / development engineering, associated tooling and setup charges, and low production volumes. Programs acquiring FPDs that correspond to standard commercial sizes can typically realize initial acquisition cost savings by employing consumer-grade FPDs. Direct comparisons are difficult because programs do not use common FPD systems. However, rough cost estimates were provided to the IDA study team for the front end of an avionics display, or "display head"—the FPD, backlight, and drive electronics (but no processing electronics). The cost of a display head employing a custom FPD was typically about 50% higher than one using a consumer-grade FPD. Rough approximations of the differences in cost between consumer-grade and custom FPDs might range from $10,000 vs. $6,000 for a 6x8 inch display; to $6,000 vs. $4,000 for a 4x5; and $4,000 vs. $2,500 for a 3x4. All FPD systems using consumer-grade FPDs were supplied on fixed-price contracts, with development costs amortized over the contract. This practice is increasingly becoming the norm for both custom and consumer-grade FPD systems.

Many Service acquisition programs have exhibited cleverness and creativity in using the flexibility afforded by defense acquisition reforms to meet their short-term FPD needs. Indeed, programs experiencing some of the greatest difficulties and cost overruns in the integration of FPD technology into their platforms were those who adopted a more traditional and rigid approach to requirements specification and supplier management. But these decisions largely do not address the fundamental uncertainties and strategic risks facing programs, whether they are using consumer-grade or custom.

7. FPD STRATEGIC ISSUES

The findings on LCC are linked to broader issues of technology strategy and acquisition policy. The LCC implications of FPD technology are determined primarily by mission performance, commonality, and availability, none of which can be adequately addressed at the level of the individual program. The relative lack of LCC consideration across programs implies the presence of general acquisition barriers. This study highlights some issues associated with the implementation of DoD's acquisition reform.

FPD acquisition also raises technology and industrial base management issues beyond those addressed by recent reforms. Because FPDs promise significant improvements in defense systems capability, it would be risky for DoD to sit on the sidelines. Failure to incorporate FPD capabilities could reduce the technological advantage of U.S. defense systems. But the FPD acquisition problem cannot be overcome by simply removing barriers to the integration of COTS.

With respect to LCC, the heart of DoD's FPD acquisition problem is low volume and long development times. Amortizing development efforts over low volumes raises unit costs, especially for an emerging technology such as FPDs where manufacturers face a long and difficult learning curve before product yields reach viable levels. Long development times make obsolescence problems more pressing. Being a relatively immature technology, FPD technical evolution and future costs are very uncertain, and application data is sparse. DoD could waste a lot of money by committing prematurely to existing technology. Stretching already low volume purchases out over many years makes it difficult to sustain an industrial base. Also, while DoD must rely on commercial industry, it would be imprudent to become wholly dependent on unproven suppliers.

7.1 OPEN SYSTEMS

The term "open systems" refers to an integrated technical and business strategy that defines key interfaces for a system. Use of stable, well-defined, standard interfaces between subsystems gives developers flexibility to take advantage of performance and cost improvements in underlying technologies with reduced redesign and requalification of other parts of the system. Increased use of commercial items enabled by open systems can achieve savings by avoiding duplication of development and by reducing production costs.

Achieving such flexibility requires significantly more effort and expense than simply designing to currently known technology. Designers must attempt to predict the development of key technologies by using market analysis and technology forecasting tools. They must then partition their system design so that the resulting system architecture anticipates upgrades of certain sections without requiring the remaining sections to be redesigned. The architecture must include careful definitions of geometrical, electrical, and software interfaces so that changes in upgraded sections will require minimal changes to the rest of system. The physical design also needs to include sufficient tolerances to enable the insertion of new technologies or substitution of alternate sources. This means that designers must describe the subsystem behavior and its operating environment in greater detail than would otherwise be necessary, and the description must be maintained in a form compatible with evolving commercial technology and practices.

The potential savings on a display head cited in Section 6.2 are relatively small compared to those available when an open systems approach is used and a display integrator is given the opportunity to insert commercial products and make changes without affecting the configuration provided to the government. Coupling an open systems approach with having the display integrator maintain configuration control enables maximal use of available commercial products while giving the integrator the needed flexibility to adopt the display system to changes in commercial products.

While this approach may result in less tightly integrated systems and hence less than maximum performance, the cost savings can be dramatic. For example, Honeywell offered a price reduction from $43,000 to $30,000 on the FPD display LRU for the CH-147 transport in exchange for control of the display system configuration. However, in the current budget environment, programs do not have and find it difficult to obtain the extra funding necessary to make the non-recurring investments necessary to implement an open systems architecture. They also do not have resources available to monitor evolving commercial technology and participate in standards development. As a result, few of the display integrators contacted by this study have adopted an open systems approach. Notable exceptions are the Bradley and Abrams programs which are using open architecture approaches with the aim of providing more assured and affordable upgrade paths.

7.2 COMMONALITY

In the case of FPDs, standard driver and display system electronic interfaces are particularly important to supporting commonality. Well-defined display system interfaces would make it easier to replace FPDs either for upgrading or to deal with obsolescence. Greater commonality would allow decidedly larger acquisition savings due to even higher volumes and greater shared development. Significant ownership cost savings are also possible due to common maintenance and training facilities. Commonality could reduce (but not eliminate) the costs associated with low-volume purchasing.

Despite these potential benefits, use of common architecture standards across platforms is rare. The main problem is that programs have few incentives to work toward commonality. Program managers are rewarded for meeting individual performance, cost and schedule targets. The advantages of coordination with other programs are typically outweighed by performance compromises, the costs of coordinating development, and schedule risks. The more compromises contained in an agreed standard—e.g., if it represents the "least common denominator" among programs—the less useful it will be to individual programs. Program managers may still need to spend significant NRE dollars on system integration. Also, because programs do not generally coordinate development schedules, the program managers come to the table having made design commitments that can be expensive and risky to reverse. For example, the Apache FPD program was able to save money based on lessons learned from the earlier F-22 FPD effort. Adopting the F-22 FPD system without adaptation would lead to much higher costs for Apache. Similarly, F-22 would face large redesign costs to adapt Apache's approach to its system. These redesign costs could not be justified due to the small number of displays needed by F-22. Both programs would face schedule risks by changing course. More importantly, they would make their success dependent on another program. Program managers are averse to ceding control on matters that will be an important part of their evaluation.

Certain programs have been developed to address the disincentive for commonality. The Army's Horizontal Technology Integration efforts recognize the need for cross-program coordination, and there are several success stories. Warner Robins Air Logistics Center is leading the CLADS initiative, with the goal of taking advantage of emerging COTS FPD technologies to replace the aging and increasingly insupportable 19-inch CRT-based monitor systems used in platforms such as the E-3 AWACS, E-Joint STARS, ABCCC, and E-2C. According to the Air Force,

> Common Large Area Display Set (CLADS) is a technology insertion monitor system designed as a form, fit and function preferred spare replacement conforming to all electrical, mechanical and operator interfaces on the specific platform. The CLADS is designed to be both technology and vendor independent allowing any technology display and vendor to compete as the production source. The CLADS will be procured using system performance based specifications, detailed specifications and an information data package...The initial Air Force (AF) buy will be approximately 500 units with requirements expecting to generate an additional requirement of approximately 1,500 units. The Navy and Army are expected to generate an additional requirement of approximately 12,000 units.[35]

However, due to the immediate need for portable, high-resolution workstation-sized flat-panel display devices, the Army's PM-CHS has elected to procure two commercially available flat-panel displays. At 1280x1024 resolution, weighing less then 25 pounds, these 16-inch and 20-inch versions meet the Army's portable workstation sized display requirement.

7.3 AVAILABILITY

Availability is closely related to commonality. Greater commonality means higher volumes and a more robust market, which reduces the probability of obsolescence or lack of supply due to business failures. Much of the debate concerning the use of custom vs. consumer-grade FPDs centers on the availability issue. Some point out that the cost of replacing obsolete consumer-grade FPDs can eliminate the initial advantages in acquisition cost. By managing its supply chain more closely, DoD could realize lower LCC due to smoother product transitions and sound configuration control. Integrators using consumer-grade FPDs counter that the high MTBF of FPD systems should make the need for replacement rare. If resupply is needed, their experience has

35 “Sources Sought Synopsis,” *Commerce Business Daily*, 25 September 1996.

been that older FPD products have continued to be available for extended periods, and that the foreign manufacturers with whom they have worked have always either made alternative products available or provide sufficient notice for life time buys to be arranged.

Having a platform disabled due to lack of a replacement part is the primary cost of unavailability. In the worst case, the platform can be disabled for as long as it takes to redesign and remanufacture the FPD system, which could be years if there were no existing suppliers for the particular FPD needed. Hence, lack of FPD availability is not only a potentially expensive problem for defense programs but also a strategic risk.

A strategic availability issue is the viability of domestically based custom FPD producers, given the inroads into the military market made by display integrators using consumer-grade FPDs. Some believe that, until the FPD market matures and stabilizes, it would be imprudent for DoD to put itself in a position of being dependent on foreign, commercial FPD producers. In addition to LCC concerns raised above, there are two strategic rationales for this position:

- It was only three years ago that DoD invested in domestic FPD suppliers because of a stated unwillingness of foreign FPD producers to work with defense integrators, not to mention Japanese laws that prohibit supplying the U.S. military. The current supply arrangements that certain display integrators have with foreign FPD producers are possible only because avionics FPD systems are considered "dual-use" products; i.e., they are predominantly used in commercial aircraft. This dual-use arrangement does not apply across the spectrum of DoD needs.

- In the future, consumer-oriented FPD manufacturers may no longer be responsive to DoD needs. For instance, the willingness of foreign FPD manufacturers to work with U.S. display integrators may be due to the current economic conditions and manufacturing overcapacity in Asia. When these conditions change, these relationships may no longer be economically viable. Another possibility is that stand-alone FPD producers may be absorbed into vertically integrated companies that provide differentiated solutions combining FPDs, electronics, and software. These companies may no longer sell components to U.S. display integrators.

Because of the tight integration of the FPD, electronics, and software in determining display system performance, the type of vertical integration expected by some in the community would be sensible from a technical point of view. It is unclear whether the supply relationships being developed by other display integrators will achieve the level of technology sharing and cooperative planning achieved by Rockwell and Sharp.

Using only domestic custom FPDs will not necessarily lead to an assured supply for DoD as there are reasons to be concerned about viability of current domestic custom FPD fabricators. OIS, the major domestic custom producer, has sustained substantial losses, about $30 million in 1997, and is projected to lose a similar amount this year. Its major problem is that it has not generated a broad-based commercial demand for its products. As a result, OIS is rethinking its approach to the display market. Another U.S. firm, dpiX, is offering custom FPDs for meeting military requirements. dpiX has a more broadly focused commercial market focus than OIS, but it is also a very new firm that only now is entering into production. Meanwhile, over the past two months, two North American producers of custom FPDs, Image Quest and Litton-Canada, have ceased production.

Another key uncertainty is the future of FPD technology. Several new approaches—most notably Field Emission Displays (FED) technology—could contend with AMLCD in some applications. Certain of these technologies, if successfully developed and economically viable, promise to be much easier to customize for military applications than AMLCD. But it will likely be at least five years before the commercial future of these technologies is known.

In the final analysis, DoD is currently dependent on foreign FPD suppliers to the extent that many third-party integrators rely upon FPDs from foreign commercial sources. However, because FPDs are manufactured by several foreign sources and production is dispersed, this dependency does not raise immediate vulnerability issues. If, for some reason, foreign suppliers become unwilling or unable to provide displays, the domestic FPD production base probably could, if given enough time and resources, be expanded to meet DoD needs. On the other hand, DoD could become vulnerable with regard to custom FPDs, at least in the short term. Because foreign commercial FPD manufacturers will not necessarily provide custom FPDs to meet stringent military requirements, DoD would face serious supply problems if the domestic custom FPD suppliers were unable to stay in business. Longer-term, alternative technologies being developed by DoD and others may substitute for or replace the AMLCD technology on which DoD currently relies.

8. CONCLUSIONS

8.1 NEAR-TERM SITUATION

Around 1990, initial DoD efforts to incorporate the emerging FPD technology into military systems were development programs that sought to push the existing FPD technology to meet DoD's demanding needs. At that time, commercially available FPDs, domestic or foreign, were not capable of meeting these needs. Until this year, there were serious problems in acquiring FPDs for military applications, due in large part to difficulties in the production of custom FPDs. Many programs were faced with the prospect of platform delivery delays due to an unavailable FPD system. Programs with particularly stringent FPD requirements or lack of alternative sources worked directly with custom FPD producers and display system integrators to overcome these problems, but at considerable cost.

These initial delivery problems opened the door for display integrators who specialized in ruggedizing consumer-grade FPDs. Programs with flexibility in their requirements relaxed their performance specifications in order to keep on schedule. The programs report satisfaction both with the environmental tolerance and optical performance of the delivered systems.

Thanks to the efforts of program offices, prime contractors, and display system integrators using both custom and consumer-grade FPDs, DoD does not presently have major FPD supply problems. While two custom firms have exited the business, the production problems at OIS appear to be resolved at this time. Another U.S. firm, dpiX, has emerged as an alternative source of custom FPDs. At the same time ruggedized consumer-grade FPDs are providing satisfactory performance in a wide range of applications.

8.2 LONGER-TERM PERSPECTIVE

DoD faces both cost and availability risks in the future acquisition of FPDs. Life cycle cost (LCC) issues for FPDs have not been given concerted attention. Few programs perform detailed LCC analyses, and LCC is rarely a primary selection criterion among alternative FPD systems. Programs are much more concerned with initial acquisition cost than with LCC. They have few incentives to adopt open systems architectures or work toward commonality in FPD systems. By and large, FPD evaluation and insertion are being performed program by program. While there is some cross-program learning, this process does not appear to address the problems of inserting an emerging technology in a sufficiently systematic manner. DoD resources could be more effectively spent if there were a more coordinated cross-cutting approach to acquiring FPDs.

Likewise, FPD availability is not assured due to uncertainties as to [1] continued access to foreign consumer-grade FPDs, [2] the economic viability of domestic custom FPD suppliers, and [3] the technical and market success of future FPD technologies. The cost of replacing installed FPD systems (or completing current production runs) could be very high if the present supply arrangements are disrupted.

8.3 DoD Investment in FPDs

The primary investment and management decision facing Congress and DoD is the extent to which individual programs are left to solve their particular technology application and supply problems on their own. Our findings suggest that certain types of cross-cutting investments and coordinating activities, if well managed, could provide superior results toward mitigating long-term supply uncertainty and promoting life cycle affordability. Acquisition policy for FPDs could benefit from attention and leadership at a level above individual programs or military services.

It would be helpful for DoD to support programs in making sound long-term technology choices through greater participation in standards development, defense technology roadmapping, and coordinated test and evaluation of emerging FPD technologies. Individual programs do not have resources available to accomplish these tasks.

The commercial market tends to select standards that are best for the largest number of users. These standards will vary in how broadly they are accepted and how widespread they are in use. DoD could benefit from being active in consolidating its technology interests and representing them in non-governmental standards forums.

DoD would need to commit to standards development as an ongoing activity in order to keep up with technical evolution.

DoD Instruction 5000.2-R encourages the pursuit of open systems as both a technical approach and a preferred business strategy in the acquisition of FPD systems and components. FPD acquisitions should endeavor to utilize commercial, consensus-based open interface standards and open systems design approaches wherever possible. Appropriate use of open systems approaches can help ensure that DoD is not unduly locked into any particular technology or vendor and that DoD programs can cultivate multiple commercial sources of supply as well as facilitate technology upgrade and enhance FPD supportability.

Technology roadmapping supports these efforts by helping to capture and disseminate DoD interests. It can also help to define the key interfaces across which commonality should be sought, with a view toward minimizing the initial performance penalty individual programs face in adopting a common standard. More importantly, it can provide programs with helpful technology and market analyses and forecasts. For example, strategic concerns about FPD availability are based in part on uncertainty about the future of FPD technology. Several new approaches—most notably Field Emission Display (FED) technology—could replace AMLCD in many applications. Certain of these technologies, if successfully developed and economically viable, promise to be much easier to customize for military applications than AMLCD. It likely will be at least five years before the commercial future of alternative technologies is known.

DoD has also benefited from programs that provide funds to pay the non-recurring engineering costs associated with qualifying commercial technology or converting to an open systems architecture on a specific system. In the current budget environment, programs do not have and find it difficult to obtain the extra funding necessary to make the non-recurring investments to implement an open system architecture.

Consolidated DoD demand for FPDs is still small relative to the investments needed to sustain an emerging technology such as FPDs. Hence, continuing support for FPD technology development will likely be required for some period, especially to address the production problems that can be the major barrier to the success of an evolving technology.

8.4 MANAGEMENT OF FPD ACQUISITION

Without changes in acquisition management, the effectiveness of cross-cutting investments will be diminished. Good technology roadmapping should support involvement in setting standards. Standards development efforts could be wasted without coordinated funding for legacy programs to convert to an open systems architecture. Open systems architectures will not see widespread use if the disincentives for commonality are not overcome. Commonality will be difficult to achieve without well-coordinated test and evaluation and the ability of programs to adjust their development schedules to take advantage of lessons learned. Without more commonality and concomitant higher volume purchases of standard parts, sustainment of a responsive supplier base could be impossible.

Continued development of the Integrated Process Teams (IPTs) approach can help programs recognize and resolve system life cycle tradeoffs. The Army's Force XXI concept expands this concept to include continuous experimentation with novel combinations of technology, organizations, acquisition practices, doctrine, training, and support. The "learning by doing" approach inherent in Force XXI is particularly useful for investigating evolving technologies such as FPDs. Such a process can help overcome the concerns integrators have voiced about ambiguity of requirements, inappropriate waivers, and the resulting concerns about the overall fairness of the source selection and contracting process. It is also a step toward institutionalizing the type of learning that occurs only on an *ad hoc* basis today. Such institutionalization could help make all participants "owners" of LCC concerns. Wider LCC consciousness could help overcome the fact that DoD program management responsibilities are typically handed off from one manager to another over the course of the system's development and operation, which makes it difficult to maintain a unified, long-term approach to upgrade management. The process can also provide early insight into new technologies, which can contribute to active standards development.

As with other life cycle issues, such as the encouragement of commonality, the issue of assured supply requires attention and leadership at a level above individual programs or Services. High-level leadership could help develop mechanisms and incentives for cross-program and cross-Service cooperation in evaluating and developing rapidly evolving technologies. Today, if a program manager perceives a long-term advantage in changing development and production schedules to coordinate better with another program, there is no high-level advocate to turn to for support.

Part III
Appendices and Supporting Data

APPENDIX A: MILITARY ENVIRONMENTAL AND PERFORMANCE REQUIREMENTS

Chapter 3 addressed the main aspects of environmental and performance requirements that are of concern in inserting FPDs into military applications. This appendix provides more detailed discussion of these military environmental and performance requirements, focusing on what measures are taken to achieve the needed capabilities.

TEMPERATURE

Defense Requirements

Critical high performance equipment must be able to operate under both extremely hot and cold conditions. In fighter aircraft, for example, displays must function well enough at high or low temperatures to permit immediate monitoring of critical parameters, such as engine start-up and operation, validation of navigation aid performance and overall system status. Draft Air Force standards recommend that a display module should achieve 25% of specified luminance to display imagery at a 1 Hz update rate within 30 seconds of turn on from cold soak at -54°C and to attain full performance levels within 300 seconds. Tests on F-16 and F-18 aircraft parked in the desert with the canopy closed and direct solar radiation on the display surface show that temperatures reach 90°C on the FPD surface and 110°C inside.

During operation of the display, cockpit temperatures are necessarily limited because of the presence of the aircrew. Nevertheless, thermal management within the display is important, since the high luminance requirements and the low transmission efficiency of AMLCD displays means that significant amounts of heat are generated inside the display. The lack of forced air-cooling in some fighter cockpits exacerbates this problem. As an example of typical practice, F-16 multifunction displays must be capable of 2 hours continued operation at 71°C. Temperature sensors are included inside the display and if the measured temperature exceeds 102°C, the backlight power is reduced until the temperature falls below 95°C. This thermal protection can be over-ridden by the pilot in critical situations, as custom-built displays can operate at over 105°C for short periods.

For military transport and scheduled reconnaissance flights, requirements closer to those of commercial aircraft may be sufficient. Initial operation is typically required within 5 minutes of turn-on and full performance within 15 minutes, starting from a temperature of -40°C. In closed Army vehicles on the ground, temperature extremes of -50°C and +70°C are experienced and no forced air circulation is available for cooling. Temperatures on board naval vessels are moderated by the presence of the ocean and even for ship-based helicopters, ranges of -40°C to 55°C are typical. Less temperature variation is needed for displays carried on land by personnel, such as head-mounted or weapon-mounted displays or the screens in portable computers.

Meeting the Requirements

Low temperature operation can be achieved by providing a prompt, uniform heating mechanism for the LC material, such as an ITO heater glass laminated to the LC cell using an optical adhesive with good thermal conductivity. Backlights must also be heated in order to emit efficiently at low temperatures. Custom AMLCD manufacturers have the additional flexibility to choose an LC material with a low freezing point.

For operation at high temperature, good thermal management of the backlight assembly and LC cell is essential to maintain the LC temperature well below the clearing point, at which images cannot be formed. High temperatures also change the pretilt angles formed by the alignment polyimide. Display integrators using consumer-grade AMLCDs can extend the temperature range well beyond the normally specified range of 0°C to 50°C. However, for temperatures around 90°C and above, custom manufacturing is essential so that appropriate materials can be used within the LC cell. Custom manufacturers have the option of using LC materials with higher clearing points and polyimide materials that maintain contrast over a wider temperature range. The selectivity of standard polarizers decreases rapidly at high temperature but the use of non-iodine polarizers can ameliorate this problem. Operation for long periods at high temperature leads to image retention problems. These can be compensated by adjustment of the driver algorithms.

The most prominent effect of long-term storage at high temperatures is degradation of the polarizers. Moisture control during manufacture and sealing integrity are essential to the prevention of delamination. Standard optical adhesives become yellow or brown at high temperature and so must be replaced by variants without this defect. All glues, seals and adhesives must retain their strengths at high temperature. Film delamination, seal failures and buckling can also be caused by thermal shock. Glass edges must be crack-free, since microcracks will grow rapidly under thermal shock. These problems are encountered both within the LC cell and outside. Problems inside the cell, such as shear between the active and passive substrates or the cracking or peeling of microstructures can be prevented only by the original manufacturer.

AMBIENT LIGHT

Defense Requirements

The illumination levels in open land vehicles, ship bridges and aircraft cockpits far exceed those of a typical office or home environment. At the extreme, strike fighters usually have a transparent, bubble canopy. This provides all-round visibility, but allows far more light into the cockpit than in a civilian or military transport airplane. Many military applications require displays that are readable in sunlight conditions.

Ambient light reflected off the display surface can mask the light emitted by the display. Reflection is of two types: diffuse (scattered in all directions) and specular (reflected in a specific direction). Both effects must be taken into account in display design. Two parameters are usually given to specify illumination conditions.

> **Example 1.** Full daylight for an open cockpit is usually taken to be a luminance of 10,000 foot-candles (fc) directly onto the display, together with a luminance of up to 2000 foot-lamberts (fL) at the specular angle with respect to the viewer. These values are used for both fixed wing aircraft and helicopters[1].

> **Example 2.** For soldier portable displays that must be sunlight readable, an illumination level of 8000 fc is anticipated. This level is also often assumed for commercial aircraft. Even with the hatch open, the amount of sunlight reaching displays in Army ground vehicles is less. For example, for the Abrams tank, it has been estimated that the ambient light level exceeds 1500 fc for only 1% of operational time. In the Bradley Fighting Vehicle, luminance levels of 5000 fc are expected, because light can enter through the commander's hatch and

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1 Foot-candle (fc) and foot-lambert (fL) both refer to one lumen per square foot. fc is used for illumination and fL for surface brightness.

through the rear of the vehicle. Levels around 1000 fc are assumed for the multiple-launch rocket system (MLRS).

As well as operating at these high light levels, many displays are also used in dark moonless nights, at ambient levels down to 0.1 fc. The brightness must therefore be adjustable by a factor of 100,000. When used in conjunction with night vision goggles, the amount of infrared light emitted by the display must also be limited.

In addition to the immediate effects of reflected light on display visibility, sunlight also contains UV radiation that can lead to long-term deterioration of display performance. This effect is minimized through UV filters.

Meeting the Requirements

In order to ensure that displays can be seen clearly in bright sunlight, the contrast between the light emitted by the display and the reflected sunlight must be high. Even in displays which do not rely entirely on creating their own light but also make use of reflected sunlight in forming an image, the display must be able to modulate the reflected light so that parts of the screen appear black. The various means by which the luminance (brightness) of the emitted light is enhanced are discussed below. Here we will examine how the reflected light can be minimized. This is important to reduce the thermal load on the display as well as increasing the contrast.

To determine the intensity of light that is reflected by a surface to one's eye, one needs to know two parameters, the specular reflectivity, referring to light that bounces back as in a mirror in a single direction, and the diffuse reflectivity, describing the proportion of light that is scattered back in all directions, as off a rough surface. In the lighting conditions of an aircraft cockpit in bright sunlight, the total reflected light intensity is about 50 fL, which is higher than the maximum brightness of many notebook displays. This reflected light level is reduced to around 20 fL in most custom LCDs.

There are five major contributors to the reflection of external light. The first three can be improved by ruggedizers of consumer displays, whereas the last two must be tackled during the manufacture of the LCD cell. In all five aspects, reducing the reflectance without compromising other performance parameters means using more expensive materials, both for the ruggedizer and custom manufacturer.

- Cover glass: Reducing the reflectance of the outer glass surface is critical. Consumer displays often use a coating on top of the polarizer, but the reflectance of these materials is usually 0.4-1%. Ruggedizers and custom suppliers use anti-reflective cover glass with specular reflectivity between 0.1% and 0.5%.

- Polarizers/retarders: The interface surfaces between the polarizer and retarder leads to reflection because of differences in refractive index between these two optical films and the pressure-sensitive adhesive. There is currently little difference between ruggedized COTS and customized displays in this respect.

- Lamination adhesive: The adhesives used to laminate the front cover glass and heater plate affect both specular and diffuse reflectance. Flexible, gel-based lamination materials and air gaps often lead to high diffuse reflectivity.

- Black matrix material: Coatings with low reflectivity are applied to all non-transparent surfaces in both the color-filter and TFT plates within the LCD cell. Black matrix materials in consumer displays typically have specular reflectance between 0.7% and 2%, whereas custom suppliers can use more expensive materials with index below 0.5%, which is important for achieving sunlight readability.

- Color filter material: The optimum choice of color filter type depends on whether diffuse reflectivity or specular reflectivity is more critical. In comparison with the standard dyed gelatin or polyimides, dispersed pigment color filters scatter more light and thus have lower specular reflectance but higher diffuse reflectance. The selection must be made by the cell manufacturer and cannot be changed by the ruggedizer.

Another effect associated with long-term exposure to sunlight is UV damage. The extinction ratio and efficiency of polarizers are degraded by UV radiation and the polarizer material may turn yellow or brown. These effects can be ameliorated by proper selection of polarizer material and lamination assembly process. Techniques such as auto-clave or pre-bake can be used to give enhanced protection to standard commercial polarizers.

Most of the damaging effects of UV light occur within the LC cell. Dispersed pigment materials give much better resistance than dyed gelatin or polyimides. UV irradiation of alignment polyimide lowers the pre-tilt angle of the LC molecules, leading to reduced contrast ratio, image sticking, slow response times and increased non-uniformities. Finally, the LC material itself degrades and does not twist in the way required for light modulation.

Dimming range and compatibility with NVIS requirements depend mainly on the design of the backlight systems and its power supply. When very wide dimming ranges are required, it is common to provide two backlights, one for operation in sunlight, the other for night-time use. The main design rules for NVIS compatibility are:

- Spectral transmittance: Color and monochromatic displays have special requirements for data relationships to specific colors. NVIS specifications mainly focus on red for failure information and yellow for warnings. To standardize panel instruments, the green filter should also be matched to the required chromaticity. The spectral transmittance needs to be matched with the backlight spectrum to produce the desired colors.

- NVIS filtration: All optically transmissive materials should be optimized for visible light and the passage of IR wavelengths should be minimized. This is achieved by selecting materials that absorb in the IR or by optimizing the thin films to reflect the IR radiation while transmitting visible light.

- Fluorescence: Some materials emit IR radiation when illuminated by UV or visible light. All materials must be tested for this fluorescence. If UV->IR fluorescent materials are unavoidable, a UV filter should be inserted in the optical path.

VIBRATION AND SHOCK

Defense Requirements

Displays in military aircraft, ground vehicles, ships and submarines are subject to a wide variety of mechanical shocks and vibrations, including sustained vibrations and sudden effects associated with gunfire or being kicked or dropped. These are extremely difficult to characterize in detail. For example, the vibrational stress on an instrument within a surface ship varies significantly with position in the vessel and even from one rack to another at a given location.

There are several ways of testing the ability of displays to withstand shocks and vibrations. In the qualification of FPDs for the F-16 program, the displays were subjected to both random and sinusoidal vibrations at several levels. For random vibrations, the custom-built LCD was subjected to 6g RMS for 5 hours, 3.8g RMS for over 500 hours, and 2.1g for over 600 hours. In testing against regular sinusoidal vibrations, continuous vibrations were imposed at six different frequencies between 90 Hz and 1000 Hz, each for a dwell time of 9 minutes. Other procedures are more empirical, such as the six-foot drop test.

Severe thermal and pressure shocks must be anticipated, particularly with respect to aircraft decompression. In some cases, continuous performance is demanded; in others, only recovery is needed.

Meeting the Requirements

The display driver assembly packaging contains the most critical elements with respect to mechanical stress. The TAB (tape automated bond) bend window and die interlead bonds are especially fragile. The bend window consists of fine copper leads ranging from 0.75µm to 105 µm wide and provides the electrical connections between the LCD cells and the printed wiring board (PWB). The relative position of the boards and the glass must be tightly constrained. This requires the use of substantial frames or other constraining methods. The thermal expansion coefficients of the boards and glass must also be well matched. A protective coating is usually applied to the dies and bend windows.

The laminated cell construction is the second essential aspect of shock protection. The heater and cover glass must be attached with adhesive to the LC cell to prevent polyimide damage. The use of air gaps between the cover or heater glass and the LC cell should be avoided if the display must survive explosive decompression, since the resulting pressure differential will usually destroy the edge seals.

Thirdly, the liquid crystal construction techniques are important to minimize cracking and peeling as follows:

- Proper TFT metal deposition to provide good nucleation sites and low stress metals
- Use of adhesion additives in the color filter material and the use of cross-linked polymers
- Appropriate glass treatment prior to depositions
- Proper spacer distribution and press force to prevent spacer movement that destroys the polyimide alignment
- High strength LC glue seal capable of minimal LC contamination and low stress production
- Common crossover materials, processes and redundancies to prevent open crossovers under stress

CONTAMINATION

Defense Requirements

Since liquid crystal materials are finely optimized for their electrical and optical properties, they can be very sensitive to humidity and salt fog. Displays used on surface vehicles or by dismounted soldiers must withstand rain and sand storms, and they should not be disabled by fungus. Immersion in water or other liquids must be anticipated for many applications, and displays may come into contact with various solvents.

Meeting the Requirements

Since several of the materials used in AMLCD fabrication are either hydrophilic or permeable to water, the humidity requirements present a formidable challenge. Beginning with the liquid cell itself, it is essential that the integrity of the glue seal and fill port be maintained. This is accomplished by:

- Using humidity tolerant glue seal and fill port chemistries
- Using barrier materials to protect the glue seal and fill port

- Minimizing stress on the seal and port
- Using glue seal catalyst chemistries that minimize hydrolytic reactions due to the applied potentials
- Elimination of hydrophilic alignment polyimides and nitrides in the glue seal area

Polarizers also are degraded by exposure to humidity. The effect can be minimized by the proper design and material selection for the heater, cover glass and lamination adhesives, the use of seal barrier materials and by cutting back the polarizer edges in a manner that does not cause delamination.

Excess humidity can also lead to delamination between the different materials and to the breaking of electrical contacts. Metals in the TFT plate, PCB and connectors must be passivated and/or protected. Passivation is also needed to prevent dendritic growth of metal salts and subsequent shorting due to exposure to salt fog.

Seals and the electronic packaging are clearly the most critical concerns with respect to other contaminants, such as sand or dust. The outer cover glass must be hard enough to avoid abrasion.

INTERFERENCE

Electromagnetic isolation is important to all critical components of modern electronics systems. Display quality should not be degraded by external electromagnetic radiation, and electromagnetic emissions should be controlled in all frequency ranges. The requirement of insensitivity to voltage fluctuations of 200 v/m, imposed for some applications by each service, is a major constraint on display design. Minimization of these emissions is particularly critical for head-mounted displays.

SIZES AND INTERFACES

Defense Requirements

The size and aspect ratio (AR) of most displays are decided at the system level. For example, a display system will be allocated a certain space budget within a cockpit. There are 120 different sizes of display in the Wright Laboratory catalogue, 85 of which are only found on a single platform. Most commercial FPDs are rectangular in a "landscape mode" with AR of 4:3, 5:4, or 16:9, whereas many of the displays installed in military vehicles are either square or in "portrait mode."

The number of pixels in consumer displays is continuously increasing. Changing digital signals from one pixel configuration to another leads to image degradation. This causes particular problems for displays that are closely coupled to sensor systems such as infrared detectors.

Meeting the Requirements

Even producing a standard size in "portrait" rather than "landscape" mode requires negotiations for a special fabrication run, so that the LC molecules can be aligned in a different direction. A limited number of square sizes are available, because of custom manufacturing for commercial aviation applications. The number of display sizes that are available, consistent with these standard aspect ratios, is increasing. However, experience with the notebook industry shows that old sizes may be discontinued as new ones are introduced.

There are clearly pressures within the commercial display industry to move towards greater standardization in both display size and in electronic interfaces. However, the industry is immature and has not implemented a comprehensive set of standards. To promote its interests in display technology the Department of Defense needs to be involved with industrial associations to develop such standards.

BRIGHTNESS

Defense Requirements

The primary performance parameter for a sunlight readable display is image brightness, the required level being determined by the ambient light conditions and display reflectance. Adequate contrast must be provided in high ambient light conditions for acceptable gray scale performance and for color saturation efficiency.

Assuming a typical cockpit illumination of 10,000 fc and a reflectance of 4%, close to that of flat black paint, the intensity of reflected sunlight would be 400 fL. To produce a white image brightness of at least three times this level, a luminance of 1200 fL is required. This is much larger than most consumer displays, and lower levels of around 200 fL are often accepted, with other steps then necessary to improve contrast and reduce reflectance. However, recent test flights with AMLCD displays on F-18 aircraft have shown that luminance levels of 200 fL are insufficient when the pilot's eyes are diverted from looking out through the cockpit down to the instrument panel.

Luminance levels of about 50-100 fL have been deemed sufficient for both multifunctional color and monochromatic FLIR displays in Army ground vehicles. Lower values are acceptable in screens that are not viewed in sunlight. For example, 40 fL is the goal for the brightness of the Common Large Area Display System (CLADS) to be used for Command, Control, Communications, Computers and Intelligence (C4I) in the rear of surveillance aircraft, such as the E-3 Airborne Warning and Control System (AWACS), E-8 Joint Surveillance Target Attack Radar System (STARS) and the Navy E-2C Hawkeye, as well as in the Airborne Battlefield Command and Control Capsule (ABCCC), typically carried aboard C-130 aircraft.

The dimming range required for both sunlight and nighttime use can be accomplished with LCD displays through the use of two custom backlights, or a single fluorescent lamp with two emission modes.

Meeting the Requirements

The transmission of light through the LCD cell has major impact on the display luminance. The aperture ratio or pixel fill factor provides an upper limit on the amount of light that can be passed. OIS pioneered the design of active plates with high aperture ratio in order to meet the high brightness specifications of avionics displays. This, or similar, techniques are now being adopted by large scale commercial manufacturers to reduce power consumption for laptop computers. One element of many custom displays that has not been adapted in most COTS is the quad pixel structure, which leads to a brighter image than the common RGB stripe or triad with similar resolution. Designing the LCD cell to minimize electromagnetic emissions and to avoid the need for a special coating for EMI shielding also increases the total transmission.

Polarizers that operate by passing light with a particular polarization and thereby reduces the transmitted light by about 57 percent. This loss can be reduced through the use of polarizers that selectively reflect light. The polarization of the reflected component can then be modified and the light recycled through the system. The transmission can also be enhanced by brightness enhancement films, which work by collimating the light before transmission through the LCD cell and diffusing the light afterwards. However these films work best when a wide viewing angle is not required.

The simplest and most common step to increase brightness is to increase the power and efficiency of the backlight system. This usually increases the thermal load on the display, as well as the weight and thickness, and can increase cost. Many companies have developed backlights that are suitable for sunlight-readable displays while some are available both to custom builders and ruggedizers, others involve proprietary technology and are not widely available.

CONTRAST

Defense Requirements

Contrast requirements are determined by the minimum acceptable readability of symbology over the ambient illumination conditions. Industry standards for indoor displays are typically 60:1 at the eye reference point, 30:1 over the primary viewing cone and 10:1 at the periphery of acceptable vision. However, these goals are impractical under sunlight conditions and maximum contrast ratios of three to eight are often accepted.

Meeting the Requirements

The contrast ratio is determined both by the ability of the LCD to modulate the intensity of the transmitted light and to minimize reflected light. Minimization of reflectance has been discussed above, and involves many different steps. The range of the relative light intensity transmitted by individual pixels, often called the dark-ambient contrast ratio, is determined almost completely by the construction of the LCD cell and its matching to the polarizer/retarder film. The following factors are most important:

- Amorphous silicon thin-film transistors (a-Si TFT): The off-current (I_{off}) and voltage threshold (V_{th}) have a large effect on the dark-ambient contrast ratio. I_{off} should be less than 1 pA for avionics applications. Low TFT photocurrents are also necessary when high luminance levels are required. These factors cannot be created by ruggedization if they were not designed into the original LCD cells.

- Color filter material: The light that passes through the color filter is partially depolarized, thus reducing the selectivity of the second polarizer which reduces contrast. Custom displays use low depolarization material that increases off-axis contrast. The additional cost of these better color filter materials is being reduced so that they are being used in more COTS displays.

- Pixel leakage: Pixel leakage can result from insufficient overlap between the black matrix and ITO on the TFT and color filter substrates and can lead to significant reductions in the contrast ratio. Spacer densities above 4 per cell also increase leakage. These effects are usually more severe in COTS displays than in custom-built cells and cannot be corrected during ruggedization.

- LC material and cell gap: The LC birefringence (Δn) and cell gap are tightly coupled parameters that both depend on temperature. The cell gap must also match the degree of retardation achieved by the retarder film. Custom manufacturers have the freedom to choose materials and parameters to achieve better operation than in typical COTS displays, particularly when operation at high temperatures is required.

VIEWING ANGLE

Defense Requirements

Although many military displays are intended for a single viewer, as are laptops, the viewing angle varies significantly from one application to another. For example, the commander of an Abrams tank needs to view his display both while standing with the hatch popped open or sitting and looking out through the periscope. Since the FPDs are placed below the periscope, they are viewed from above in both positions. In other applications a wide range of horizontal viewing angles is needed, so that two crewmen can see the displays or a single pilot can view several screens in a horizontal array.

For most command and control applications it is essential that multiple viewers see the display without degradation in the contrast ratio or color discrimination. Fortunately, such displays are usually used indoors, since spreading the emitted light over a wide viewing cone usually compromises the peak brightness.

Meeting the Requirements

Viewing angle has not been a major issue for notebook displays, since they are viewed almost exclusively by a single user and the orientation of the screen can easily be adjusted. However, more commercial flat panels are now being manufactured for use as computer monitors and LCDs with larger viewing cones are becoming available. There are four ways by which the larger viewing ranges can be achieved. Three of these, in-plane switching, sub-pixellation and vertical alignment, must be implemented within the LC cell. The fourth involves the use of retardation films. These films can be added during remanufacture, but are most effective when they are matched to the parameters of the LC cell by the original manufacturer.

Since the total amount of light emitted by the display is limited, increased viewing angle necessitates reductions in the peak brightness and so may not be appropriate for use in open cockpits. It is a disadvantage to have a wide viewing angle in jet fighter FPDs, because the light out of the cockpit could be used by the enemy to locate the aircraft. The ability to focus the emitted light but to control the direction and orientation is thus valuable in many military displays. Although the viewing cone can be modified somewhat by optical films outside the LC cell, this again can be accomplished more effectively by custom fabrication of the whole display.

RESOLUTION

Defense Requirements

The most common pixel configuration in consumer-grade FPDs is currently SVGA, or 800 x 600. This is adequate for many battlefield applications. For a soldier in active combat, showing critical data in a timely and unambiguous manner is usually more important than displaying a large quantity of information. However, for command and control it is often desirable to have multiple windows open on a single display or to show great detail on large area maps. In showing data from an infrared sensor, it is more useful to have a larger number of monochrome pixels, each with 256 gray levels, than to have color capability. Also, as noted earlier, matching the display pixel configuration to a particular sensor can cause difficulties.

Meeting the Requirements

Consumer-grade AMLCDs have pixel arrays consistent with television video sources or one of the defacto laptop, desktop, or workstation computer standards for graphics displays. Only two pixel structures are available: delta configuration, for television, and vertical stripe triad, for computer screens. The military display is often a multi-function instrument that is called on to display clearly and quickly a wide variety of data from several sources: e.g., specifically-colored warning symbology, digital map data, low light TV video, and monochrome FLIR video and radar data. Display integrators using custom AMLCDs optimize pixel arrays and structures to achieve high resolution without visual aliasing effects for the needs of the specific application. In some cases, display integrators have been able to compensate for the limitations of standard AMLCD pixel arrangements through the use of specialized electronics and complex software algorithms.

POWER CONSUMPTION

Minimizing power consumption in military displays is important, to minimize heat production as well as the required power input. Great progress has been made in this respect in commercial FPD technology. Typical power requirements are appropriate for most applications where a power source is available, whether at fixed installations or on a vehicle. However, for soldier-portable displays, much more progress is needed, so that longer operating life can be attained without carrying bulky and heavy batteries. For outdoor displays, the development of reflective displays with higher contrast, better resolution and better color representation would reduce brightness requirements and hence power consumption.

COLOR

The value of color depends on the type of application. In critical combat situations, the use of a small number of vivid colors to bring information rapidly to the operators attention is usually more important than the ability to display a large number of subtle shade changes. On the other hand, for a map reader, good color shading can provide 3-D information from a 2-D chart as well as distinguishing roads from rivers. It is important that the colors be represented reliably, especially when they are used to highlight warning signals.

In the representation of infrared or radar images, it is clearly more advantageous to use a screen with larger numbers of monochromatic pixels than one with full color capability but fewer pixels. However, having the ability to display 256 gray levels is critical to achieving good sensor video images. In multifunction color displays used for FLIR data and other images, the use of "quad" pixels with RGBG structure is appropriate (though not strictly required), because the two green sub-pixels can be used for the monochromatic infrared images. Colors and gray levels can shift dramatically with viewing angle. Consumer-grade AMLCDs have limitations on retaining color and gray scale through wide viewing angles. In addition, color uniformity across the screen is another area where consumer-grade AMLCDs can have limitations.

RESPONSE TIME AND IMAGE RETENTION

The time required to register new images or remove old ones is critical for video applications, certain types of symbology, and FLIR imagery. The response time requirement for no image smearing or ghosting in a 64 gray scale image is less than 30 milliseconds. Consumer AMLCDs typically have response times of around 50 ms for inter gray scale transitions, which is not quite good enough to avoid artifacts. More significantly, the response time degrades significantly at low temperature. Adding heaters can solve this problem, but at the expense of power consumption.

Unwanted image retention can be particularly troublesome in situations where the same information is displayed for long periods and is aggravated at higher temperatures.

Appendix B: EXAMPLES OF FPD INSERTION

ASSESSING INSERTION

In the course of this study a number of interviews were conducted with flat panel display makers, display system integrators, subsystem and prime contractors, and defense program offices. Table B-1 lists the firms and DoD organizations interviewed. These interviews led to insight on how various organizations approached the insertion of the emerging flat panel display technology into particular applications. The results of these interviews have been used to develop summary discussions on the insertion of FPDs into the F-22, the C-130H, Army ground vehicles, and the Boeing 777.

TABLE B-1: Flat Panel Display Project Interviews

Industry

Avionic Display Corporation	General Dynamics Land Systems
Allied Signal	Honeywell
Battelle Memorial Institute	Kaiser Electronics
BARCO	Litton Data Systems
Boeing	Lockheed Martin
Candescent Technologies Corporation	Optical Imaging Systems
Computer Devices Canada	Planar Advance
Displays and Technologies, Inc.	Rockwell - Collins Avionics
dpiX	United Defense Limited Partnership
Electronic Designs, Inc.	

Department of Defense

Navy	Air Force
Naval Air Systems Command / Avionics Directorate	Air Force Research Laboratory / Avionics Directorate
F-18 Program Office	F-16 Program Office
Space and Naval Warfare Center (SPAWAR)	F-22 Program Office
Army	Warner Robins Air Logistics Center
TACOM- Ground Systems Integration	
Abrams Program Office	
Bradley Office	

INSERTION OF FPDS INTO THE F-22

The F-22 program adopted an aggressive approach to inserting FPDs. The Air Force contracted for the F-22 FPD system in the traditional military manner: Program management set target specifications for reflectance, temperature range, EMI, color coordinates, etc., which were generally at or beyond the current state-of-art capabilities. Hence, the contract for the display subsystem was for a development effort by the team of Kaiser and Lockheed Sanders, who then supplied Lockheed, the cockpit integrator.[2] This development effort was to be followed by "engineering manufacturing development" (EMD) and then "low-rate production" (LRP) contracts. Optical Imaging Systems (OIS) won the development contract for the display head assembly — the LC cell, laminations, drive electronics and mechanical frame — in competition against SEXTANT of France, a subsidiary of Thompson CSF.[2]

[2] Thompson CSF acquired its FPD technology through the purchase of General Electric / RCA.

OIS was paid $10.5 million to develop the display head and drivers. The F-22 is to have three sizes of FPDs: 4x3 (2), 8x8 (1), and 6.25x6.25 (3). This design was laid out in detail by Lockheed designers, down to the pixel count for each display. Full color was required, and thus AMLCD was the only viable technology at the time. However, AMLCD technology was early in its development cycle and had limited availability. In early 1990s the 10.4-inch notebook display was just ramping up in production. OIS at this time was an R&D organization that did not produce AMLCD products. It only had laboratory sample demonstration units. But the F-22 cockpit was designed exclusively for FPDs. Space was not available for CRTs. So the insertion of FPDs had to succeed — no matter what it cost — introducing a major technical risk in the program.[3]

The physical space allocated for the display system in Lockheed's cockpit design turned out to be a particularly demanding constraint. Sanders allocated space to Kaiser, which did the same with OIS. Cost-performance tradeoffs at the system or LRU level were not being entertained at this point of the development process. When OIS requested a few millimeters more space in order to greatly reduce the development and manufacturing cost, it was informed no more space was available.

These practices, combined with unanticipated difficulties due to lack of experience with a new technology, led to high costs. The decision to include built-in test capability in the driver electronics resulted in high costs. The drivers ended up being unique to the F-22 and so expensive that no other program adopted them. They also became obsolete due to technical improvements: e.g., later programs use 64-bit drivers rather than the 16-bit drivers available to F-22 at the time. Likewise, OIS was able to meet the viewing angle requirements, but it took considerable investment to achieve. Most of the work involved developing laminates, liquid crystal material, color filters, and experimenting with the spacing between the black matrix and the passive plate. Electromagnetic interference (EMI) requirements were also difficult to achieve within the optical

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[3] However, OIS had 2 prior development contracts. One was for the F-15 AMNI 4x4 high-resolution 128 color/in. OIS delivered about a dozen FPDs, which were flown and tested under a Battelle project for SAIT (now Litton). Another project was a 3.4x2.9 inch Horizontal Stabilizer Indicator (HIS). In both cases, the underlying FPD technology was well understood. Controlling the manufacturing process was very difficult—OIS could not deliver consistently good displays due to process control issues.

performance parameters required by F-22. The requirement is difficult for AMLCDs in general because the thin-film transistors are on the glass. Using a good, conductive black matrix material coated with indium tin oxide was the key to meeting the EMI spec.

Other performance specifications were eventually modified iternatively, based on what the contractors could provide. The specified color coordinates could not be met, due to problems with the color filter materials. (These color requirements had been derived from the CRT legacy and from human factors studies.) Achieving the specified contrast ratio has been difficult, and it was necessary to relax this requirement through the negotiation of waivers.

The F-22 is facing severe cost pressures and with the EMD phase now nearing completion, Lockheed is seeking to substantially reduce the cost of the F-22 display system, while maintaining its functionality. Lockheed has asked its current suppliers to find ways to reduce the cost of the current EMD system and is entertaining alternative suppliers, which may offer ruggedized consumer-grade solutions. The key issue is how the proposed alternatives (custom and consumer-grade) will be evaluated against the requirements grade of the initial display system. This next phase of the F-22 display acquisition is just beginning, and it is not clear what its outcome will be.

C-130H CASE STUDY: MILITARY TRANSPORT AVIONICS

In the 1990-91 time frame, the C-130H program wanted to use FPDs to replace electromechanical devices for attitude and horizontal situation indication. The C-130H project included six different displays. The program had determined that a CRT would be too big and not provide the capabilities for graphics imaging that an FPD would. Loral, which had provided the beam index CRT cockpit displays for the C-130, decided to “no bid” the C-130H project.

Lockheed went out on a competitive bid and received several offers. Lockheed selected three firms for a Best and Final Offer (BAFO): SAIT, Sextant, and ADC. Avionics Displays Corporation (ADC), was a start-up firm that felt it could provide the desired display systems. Since Loral “no bid” the display system, ADC decided it was in a position to bid on the project. At this early stage in flat panel development, there was no vendor that offered an off-the-shelf avionics display. ADC won, bidding a development project with the non-recurring costs included in the price of the displays to be delivered. The first delivery on the contract was a “lighting mock up” which met requirements specified for luminance, night vision goggle application (dimming and NVIS radiance), and viewing angle. This proof of concept display was delivered in January 1992. Production deliveries began in January 1993 and have been ongoing, with over 1200 display systems delivered to date.

ADC contacted OIS about obtaining displays, but the two firms were unable to agree on a business arrangement. (The ADC development program for the C-130H was occurring at about the same time OIS began its F-22 development program.) Hence, they concluded that ruggedizing commercial glass was its only option. ADC’s approach was to acquire commercially available Sharp display heads and strip them down to the glass and tabbed driver electronics. ADC built the Sharp glass back up to meet MIL-STD-810. The C-130H display LRUs can operate in –54°C to +71°C range and sustain +16G acceleration in all axes, as well as 30G ½-sine and 16G sawtooth shocks. Environmental stress screening is performed on every LRU by cooling (power off) them to –54°C, holding this temperature for two hours, and then raising the temperature to +71°C and holding that temperature for two hours. Power is then turned on to verify unit performance with a full-screen, smudge-free image within 5 minutes. This cycle is repeated ten times. ADC display LRUs currently have more than 700,000 hours in the field.

The C-130H interface requirements were largely derived from replacing the electro-mechanical devices. The optical requirements came from Lockheed as well. Lockheed’s objective was to make the entire cockpit night vision compatible. Existing displays could not achieve this. ADC had to develop optical filters achieving low ambient radiance, which sacrificed some of the red color saturation as a trade-off. ADC developed the characteristics for its phosphors, laminates, coatings, etc., and worked with vendors to have them developed (not off the shelf). The optical performance of its displays is largely the result of unique filter and backlight designs.

MEETING GROUND COMBAT VEHICLE REQUIREMENTS

The introduction of FPDs into Army land vehicles is being coordinated under the Army’s Digitization Master Plan. The Army's digitization efforts are based on the Joint Staff *C4I for the Warrior* concept, which envisions a widely distributed user-driven infrastructure in which the warrior "plugs in" to obtain information from secure and seamlessly integrated computer and communications systems. The ultimate goal is to

> "horizontally and vertically integrate the Army's diversified battlefield operating systems into an interlocking information exchange network, while also providing a heightened level of essential joint and combined interoperability within a multi-dimensional battlespace. The rapid sharing of enemy and friendly information among all digitized forces within that battlespace will provide near-real time situation awareness, enhance synchronization of combat power, and enable economy of force by making units more lethal and survivable."[4]

The Army has adopted three architectures—Operational, System, and Technical—that it will develop and implement to ensure force interoperability. These architectures are provided to materiel developers to establish a seamless information system. The Operational Architecture describes the required functional connectivity of force elements and the types and volume of data and voice traffic to be passed over each communications pathway. The System Architecture describes the physical connectivity of the information system. It includes identification of all nodes (radios, switches, terminals) with their physical deployment and the specification of such parameters as the bandwidth required on each circuit. The Technical Architecture consists of rules, standards, and protocols that must be implemented to ensure information can flow seamlessly between systems.[5]

Within this framework, the performance and environmental requirements for FPD systems vary widely for land vehicles. Most tactical and combat vehicles in the Army do not presently have a display system. The Army's Applique program will be acquiring command and control computer systems for these vehicles. The Applique display is a ruggedized consumer display designed to withstand shock and vibration stress. The requirements for display systems in the M1AR Abrams tank and M2A3 Bradley Fighting Vehicle go beyond the Applique display. They are fully integrated, mission critical items used for such things as target acquisition and command

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4 Army Digitization Master Plan, Coordinating Draft, November 1995, p. 1.

5 Ibid., p. 3.

functions. They must cope with high temperatures, high ambient illumination (when the hatch is open), large vibrational stresses, and extreme shocks when the large gun is fired.

The FPD acquisition process for land vehicles largely reflects both the differences in requirements as well as the particular personalities of the program offices and contractors involved. The following brief case studies describe the processes used by the M1A1 Abrams and M1A3 Bradley programs.

ABRAMS

General Dynamics Land Systems (GDLS), the prime contractor for Abrams, began discussions with the Army in 1989 about the insertion of FPDs. The first FPD uses were for the tank driver's integrated display and the tank commander's integrated display, using Electroluminescent (EL) technology from Planar Advance. In 1995, GDLS commenced a System Enhancement Program for the M1A2 Abrams tank. Under this program, GDLS was authorized to develop a second-generation tank commander's integrated display. This integrated display consists of a FLIR display and a separate color display.

GDLS identified a large number (>60) of potential display integrators. It was very hard to get information from these companies, due in part to intense competition among them. They also felt constrained by the fact that these would be the same companies that would be asked to bid on contracts. So GDLS talked directly to potential FPD suppliers, as well as to related academic and research organizations. They did this in order to obtain evaluation criteria to be applied to proposals that would later be made by the display integrators.

Based on these discussions, GDLS did not consider commercial AMLCDs. They felt that conventional AMLCDs would not work well above 70^{o}C or so and would fail more quickly than specified if operated in that range. Several display integrators claimed they could meet the temperature spec, but they did not explain how they were going to do it. GDLS felt that if they had accepted a proposal from a company using commercial AMCLD and then the system didn't work, the supplier could potentially void the contract by pointing out that the initial requirement was not technically feasible. At that point, the program is committed and has a schedule to meet, so they have to pay up.

OIS and Planar were the eventual winners for the color display and a monochrome FLIR display, respectively. They took responsibility for meeting the temperature spec and other particular display subsystem specs with GDLS suggesting certain technical tradeoffs. Planar also supplies three monochrome EL displays for Abrams: the commander's 5x6, the gunner's 3x5, and the driver's 4x8. Planar designed special drivers to achieve 64-shade gray scale for the new FLIR system.

Life cycle cost was a major factor for Abrams. The program office took it seriously and put money behind efforts to reduce it. The Abrams program has performed several structured trade studies looking at cost, performance and schedule. They also have built cost models to evaluate alternative designs. The resulting specifications are traceable all the way up to the mission level. The information gained during the initial investigations was used to conceive pre-planned product improvements. For instance, GDLS made the display casting – a long leadtime and expensive item – large enough to accommodate expected changes in FPD technology. Because the prime contractor must be in a position to work through issues such as these that inevitably arise as development proceeds and into field support, GDLS believes that relationships with suppliers and credibility are key. Has the supplier demonstrated delivery on spec? Will they provide accurate data for configuration management and be around to make upgrades?

BRADLEY

United Defense Limited Partnership (UDLP) is the prime contractor for the Bradley A3 to support the Army's digitization effort. The upgrade encompasses the computer system, navigation, 1533 data bus, and flat panel displays for the commander and the squad leader. These displays are intended to provide improved situation awareness for troops. (The squad leader's FPD displays are the same content as the commander's.) The FPDs will display C^2 functions, maps, two FLIRs, and a TV-type "periscope." Prior to the A3 program there were no displays on Bradleys. The FPD development program was started in 1994 and completed in 1997. Low rate production of 50 vehicle systems is to be completed in July 1998. The plan is for 1700 out of a total of 5000 Bradleys to receive the upgrade.

Bradley is a highly constrained environment, with little room for displays. The commander's display will be only 10 inches from his face. Space constraints also dictated that the display units could not contain much electronics; i.e., they must be "dumb" rather than "smart" displays. In making this decision one factor was to keep the system modular, so that the computer electronics — the "Turret Processing Unit (TPU)," "Turret Fire Control," "Target Acquisition," etc. — could be upgraded without having to change the displays. The display system is not defined as mission critical.

In determining the specifications for the EMD phase, UDLP had a study contract with Computing Devices Canada (CDC). The Bradley Program Office reviewed the spec and approved it. Many of the requirements — e.g., vibration, steam cleaning, shock, -46°C to +71°C temperature range, etc. — were flow down from the program office. However, the EMD RFP did not specify that displays had to be AMLCD or any other technology. It only provided performance specifications, such as sunlight viewability, viewing angle, etc. Litton Canada won the award for the cost-plus EMD based on UDLP and the Bradley Program Office assessments of "best value" and risk. Positives included Litton's proposal to "leverage their work on the Comanche " and the fact that they were vertically integrated. Litton had 1½ years to deliver 17 displays and some qualification units. As a result of yield and performance problems, Litton was forced to deliver an "interim" product using NEC FPDs. UDLP found the NEC display to be almost acceptable, save for deficiencies in brightness and viewing angle. The units using NEC displays passed the necessary environmental tests.

Based on lessons learned from the EMD phase, the requirements changed the LRIP. Brightness went from 100 fL at 5000 ft candles to 220 fL. A "glow source" requirement of 2000 ft candles was also added. Contrast ratio was initially 3:1 at 5000 diffuse. Viewing angle was + or - 35 degrees horizontal and 20 degrees vertical but was changed to 0-50 degree viewing cone. Double horizontal resolution was required for FLIR. However, environmental specs were relaxed, based on the NEC experience, and the requirement for double horizontal enhancement for FLIR was dropped.

UDLP released an RFP for a fixed price LRIP contract for 106 displays over about 6 months at $23,000 per display. Based on the performance of the interim NEC displays, the program office was open to the idea that the commercial capability might be good enough, although it did not meet their originally stated requirements. ADC won the contract, bidding a SVGA resolution derivative of the display they were delivering to the U.K. Jaguar program. UDLP asked ADC (and other bidders) for supporting data and conducted site visits. They also surveyed ADC's customers relative to performance. The first displays from ADC are scheduled to be delivered in the Summer of 1998.

The display LRUs will be maintained through supplier depot arrangements. The estimated MTBF is 7000 hours, longer then the MTBF for the whole Bradley system. It employs dual backlights, even though a single backlight would provide enough brightness to meet the spec. Although UDLP did not perform a formal life cycle cost analysis, they examined the supplier chain to detect areas where they would be vulnerable to suppliers exercising market power. Overall, the availability of glass was considered to be more of an issue than life cycle cost per se. They have warehoused a large supply of raw glass as insurance. A primary motivation for this approach was the need to meet a tight delivery schedule. The digitized Bradleys must be ready to enter the field in 2000.

The Bradley program office demanded that UDLP employ an open systems approach, which the broader industry favored. They received non-recurring expenses (NRE) funding to examine commercial FPDs and come up with a standard interface. UDLP personnel are participating in the TACOM Future Common Display Initiative, covering Army tracked vehicles.

INSERTION OF FPDS INTO THE BOEING 777

Boeing assembled its first technical team in 1983 to explore preliminary designs of the 777 that was to be introduced in the mid-1990s. One of the jobs of this technical team was to examine emerging technologies to determine which could be exploited to give Boeing a competitive advantage. The constraints were generally to hold costs steady and not to force Boeing into making significant development investments. The objective was to rely on the investments of the technology developer, not the technology user. Part of the task was to estimate the pace of maturity of technology so that its availability and cost would meet the needs of mid-1990s demands.

Judging that the flight deck could constitute an advantage led Boeing to pursue flat panel displays as an integral part of the 777 cockpit. Boeing felt that this could provide a significant advantage and difference over its competition. The technology choice in 1983, after evaluating the alternatives, was liquid crystal displays. By 1988, having determined that the technology was maturing satisfactorily and that producibility would not be a problem, Boeing, made the final decision to use flat panels in the 777 cockpit.

Boeing's requirements, like the military, are for high technology but with low procurement volume. Boeing's general acquisition policy is not to pay for NRE, which according to its usual business practice should be amortized in the purchase price. Consequently, suppliers retain the right to sell to other customers. Exceptions to this NRE policy are related to (1) supporting suppliers that do not have an existing business base with Boeing, (2) overcoming high technical risk, and (3) making changes in functional specifications after contract signature.

In such development efforts Boeing will commit to long-term buys where six to ten years is typical. As part of this commitment, Boeing expects that there will be a three to six percent improvement per year in cost over the life of the contract. The contract usually will guarantee a minimum purchase and will also state a maximum the supplier would be expected to deliver. This guaranteed long-term contract provides suppliers with the assurance and incentives to make the necessary investments to achieve cost reductions and to make sure the production capacity is available. The contract is typically firm-fixed price after a global competition is conducted.

In the flat panel case, Boeing's strategy was to push the technology to a point where it could freeze the specifications over a ten-year production period. As a consequence, the specifications developed by Boeing were considerably beyond the performance of the then-current technology. Because of the very advanced and difficult performance requirements (there are 400 optical performance specifications), Boeing has made NRE investments for these leading-edge screens. The technical difficulty did not seem to limit potential suppliers; there were six bidders for the initial contract. Boeing made the award for cockpit integration to Honeywell in October 1990, who in turn contracted with Hosiden of Japan to supply the flat panel displays. Deliveries commenced in 1995.

Even though to date no deliveries have been missed, Boeing is not satisfied with the cost of the flat panel displays. Lack of satisfactory yields of this leading-edge product seems to be the cause of the higher than desired cost. Boeing has chosen to bring in a second source to help with the cost problem. Boeing and its suppliers are sharing the pain to get the cost issue under control, which involves some relaxation of the technical requirements.

Boeing, also like the military, is concerned about being vulnerable to a sole source supplier, whether domestic or foreign. In the flat panel case, Boeing was comfortable that there were alternative suppliers available and in fact is now pursuing a second foreign source. Since Boeing's strategy is to rely on commercial flat panel suppliers, another dimension of vulnerability is the possibility of commercial suppliers abandoning them, as commercial production migrates to other markets. This issue is not unique to flat panels and is a fairly routine problem. The solution is that any supplier discontinuing production will provide the customer advance notice leaving two options: adequate time to find or develop substitutes, and/or final purchase to cover the lifetime requirement of the product.

Boeing's pushing the envelope of flat panel technology to create a competitive advantage in the latest generation aircraft, despite problems is paying off. The flight deck of the Boeing 777 is impressive and the airplane, by most accounts, is both a technical and market success.

Appendix C: CONGRESSIONAL LANGUAGE

Senate Report 105-29

National Defense Authorization Act for Fiscal Year 1998

Report with additional views, Committee on Armed Services, United States Senate

June 17, 1997, Page 203

"Flat Panel Display Technology"

In 1994, the Department of Defense Flat Panel Display Technology Task Force declared that flat panel display (FPD) technology was a critical technology. Because of their lower life cycle costs and improved performance characteristics, FPD systems increasingly replace cathode-ray tubes in many U.S. military aircraft and ground combat vehicles. Suppliers within the U.S. have provided highly effective FPD systems that are custom designed to meet military requirements.

The committee is aware that as a result of cost and schedule constraints, the Department of Defense (DoD) has procured some consumer-grade displays designed primarily for laptop computers, which are then ruggedized for military use. As in the case of any commercial insertion, these procurement decisions require careful analysis of life cycle cost and performance tradeoffs to ensure that military user needs are met. Quantitative data to support such cost and performance tradeoffs are not always readily available. Therefore, the committee directs the Under Secretary of Defense for Acquisition and Technology to perform a study of the environmental and performance requirements and test data on performance of both custom and consumer-grade FPD systems in various military platform applications. Additionally, this study should assess life cycle costs and support issues such as commonality, supportability, and availability of both custom and consumer-grade FPD systems. The study should specifically address the potential benefits of FPD system interface standards and open systems approaches.

The Under Secretary should submit the results of this study to the committee by March 1, 1998. Weapon system program managers shall use data from this study in FPD system tradeoff decisions, with the objective of meeting user needs at the lowest life cycle cost.

Appendix D: DoD Steering Group Members

Larry Goodell, OSD / I&CP / DU&CP (Study Co-Chair)

Bruce Gnade, DARPA (Study Co-Chair)

Charlie Bradford, Night Vision Lab

Mike Breckon, NAVAIR

David Busse, TACOM Ground Systems Integration

James Byrd, Aeronautical Systems Center

Erik Chaum, NUWC

Henry Girolamo, Soldier Systems Command

Duane Gomez, NRAD, SPAWAR Systems Center

Darrel Hopper, Air Force Research Lab

Robert Miller, ARL

Becky Morgan, NAVAIR

Ray Schulze, PM-ATCCS

David Troxel, Night Vision Lab

Susan E. Turnbach, DDR&E, Sensors & Electronics Technology

Bob Zwitch, WR-ALC, Robins AFB

Appendix E: SUMMARY OF FPD WORKSHOP

On December 16, 1997, preliminary results of the DoD FPD study were discussed and refined at a workshop attended by a broad cross-section of the domestic FPD industry and DoD participants in FPD acquisition. Participants included high level representatives from industry (including several levels of the FPD supply chain), DoD and the Services.

WORKSHOP OBJECTIVES

The primary objective of the workshop was to understand and report on the issues that were foremost in the minds of people actually working in the defense FPD business. Accordingly, the attendees included representatives from the Services, prime contractors, system integrators, display integrators, and FPD glass suppliers.

Issues for discussion were to include all aspects of the business that the participants believed to be areas with problems. Our primary objective was to provide a forum in which the participants could feel free to express themselves openly and with candor. An important second objective was to verify the preliminary assessment conclusions drawn from the field research. Participants were asked to comment on the validity of the IDA conclusions later during the discussion period.

METHODOLOGY

After opening presentations, the attendees were divided into small discussion groups, and much of their time was spent in this forum. It was felt that the small group environment would better facilitate ideas and potential solutions to problems in support of the objectives stated above. Accordingly, the open sessions were restricted to essential activities. Five small groups were asked to define their two most pressing issues affecting the defense FPD business, and recommend solutions if possible. They were also asked to comment on the validity of the preliminary conclusions from the field research.

The make-up of the discussion groups was chosen carefully with the intent that each group be balanced. Each group had at least one customer from one of the Services, one glass supplier, one display "head" integrator, one display system integrator, and one prime contractor.

FINDINGS

Prior to breaking into discussion groups a list of nine very broad issues of concern were presented. The participants were asked to vote on what they thought were the two most critical problems that needed to be addressed. A tabulation for the results is shown below in Table 1.

Table 1: Participant Interest in Issues

Issue Category	No. of Votes
Life cycle costs to DoD	10
Support for field units	4
Financial health of suppliers	4
Assurance of adequate supply regarding:	
timely new technology infusion	4
quick ramp-up	0
ongoing steady/level production	10
DoD acquisition reform	21
Ability of DoD to make sensible trade-off decisions	23
Need for DoD up front technology investments	9

Not surprisingly, the participants tended to concentrate on issues concerning life cycle costs, acquisition reform, how DoD makes trade-off decisions, assurance of supply and the need for continued DoD R&D support.

While each discussion group then attacked the issues differently, they all clustered around several common themes. There seemed to be nearly universal agreement that four truisms will greatly impact DoD's success in incorporating state-of-the-art FPD technology in defense systems. While the first three are completely beyond DoD's control, it was felt that the Department must learn to accommodate them in order to establish a better FPD strategy. These truisms are:

1. **FPD technology is still in its infancy.** Every aspect of FPD product development is still at a high level of flux, including manufacturing, distribution, cost structure, and the technology itself. To truly understand the FPD industry, one must frequently reexamine his assumptions and adjust them to recent realities. Thus, the conclusions and recommendations of this workshop must be reviewed periodically.

2. **There exists an enormous and fast growing commercial market for FPD products.** The technical requirements of this market only partially overlap the requirements of DoD. Although commercial suppliers spend significant sums on research, they can not be relied upon to provide all the product features and specifications that DoD will need. In fact, considering the unique nature of DoD's operating environments, it highly unlikely that commercial products will meet all of DoD's needs. Certainly there is a very large body of DoD requirements that commercial-off-the-shelf products (COTS) will meet, but not all. Procurement of custom FPDs will continue to be critical to DoD's success.

3. **DoD does not represent a large enough share of the market to influence main stream suppliers to provide the complete variety of products DoD needs.**

4. **In many cases DoD has let its DoD suppliers (integrators) make FPD procurement decisions.** This approach has worked fairly well, but there is concern that the issues raised in 1 and 2 above may require a more pro active DoD role in the future. A particular concern is that suppliers are being forced to make expeditious decisions that may not include assured long term support and supply.

These truisms led workshop participants to one solid conclusion that seems to override, and was the basis for their concerns in every issue area. The overriding issue is that DoD needs to take a much more formal, firm, and active role in directing FPD procurement from the top of the organization. The Office of the Secretary of Defense (OSD) needs to set aside resources to provide a coordinated thrust in this highly volatile, and critical technology arena. There are three issue areas where this effort would be particularly beneficial. They are:

ACQUISITION REFORM

DoD personnel need new universal tools and training to help them make important decisions regarding cost/performance tradeoffs and life cycle cost analyses. Another area where more training would help deals with suppliers in an Integrated Product Team (IPT) environment. This environment is a highly interactive one in which the customer (DoD), the product developer and the product manufacturer continuously discuss, and make decisions about the product during it's development and manufacture. This is a complete team effort and is quite effective at arriving at an effective product.

Additionally, program offices need the strength of the entirety of DoD's purchasing power while negotiating long term support from a supplier whose plans are in flux. Program managers also need help in determining when to best use domestic sources and when circumstances require the use of foreign suppliers.

In general, the participants felt that acquisition reform was making progress within DoD, albeit somewhat slowly. They felt the progress was in the more traditional procurement tasks, such as paperwork and inspections, and that the more leading edge procurement approaches described above were lacking.

One danger here is that when used to excess, these more leading edge skills and techniques could undermine another important acquisition reform-- increased use of performance specifications in procurement, rather than the traditional reliance on build-to-print drawings. For example, if a DoD program manager gets too deep into a product discussion with a FPD glass supplier, he runs the risk of telling the prime contractor how to build the final product, and not how the final product should perform.

LIFE CYCLE COST AND AFFORDABILITY

The participants seemed to favor a reasonably high level of commonalty and standards for FPD as a means of achieving lower Life Cycle Cost (LCC) and affordability. Additionally, they further stated that standards would surely have to be driven from the top of DoD.

There are several advantages of communality/standards. The first stems from the obvious ability to combine multiple DoD usages for larger, lower cost, purchases. The second is that with standards you can more easily specify a universal product and thus attract a wider supply base and more competitive bidding. It was thought that an important and useful adjunct of this standardization process was to establish a DoD wide technology road map to help guide technical direction decisions.

There are several concerns with respect to these advantages. The first is that it is not clear that even the total volume of DoD purchases would command lower prices; thus the commonalty/standardization process might be wasted. Secondly, typically products and technologies in their infancy tend to be very illusive to standardization. The standardization process simply takes too long and the product you were trying to standardize can quickly become obsolete.

CONTINUED DOD INVESTMENT IN FPD TECHNOLOGY

All discussion groups felt that DoD should be prepared to invest selectively in FPD technology. The workshop participants felt that investments should be considered for all aspects of FPDs. Science and Technology, manufacturing and insertion were areas that would likely need investments in the future.

The feeling was that commercial investments were unlikely to yield the range of products/technologies DoD needs to meet its many mission requirements. Stated another way, utilization of COTS is a very useful technique for many products and FPD applications. However, there are already several key DoD requirements for FPDs that commercial products simply won't meet. It is very likely that: (1) DoD's list of unique requirements will grow; and (2) commercial producers will be no more likely to be interested in meeting these unique DoD needs tomorrow than they are today.

Several participants presented examples of existing products that could have been substantially enhanced to meet unique DoD applications. However no non-recurring engineering (NRE) funds were available and the suppliers' primary customers didn't need the DoD features. The suppliers were unwilling to add them using their own development funds. Thus, opportunities to leverage a commercial product into technically superior ones at little cost was missed.

Here again, a more focused effort by DoD could probably provide some funds for FPD investments to address the short-term NRE funds issue and enable programs to more affordably and effectively meet military needs.

CONCLUSIONS

While not specifically charged with drawing conclusions, the discussion groups' comments seemed to recognize two possible approaches for DoD to proceed. One was for DoD to continue as it has and rely upon: (1) COTS; (2) the free market; and (3) its integrators' resourcefulness to provide the U.S. with affordable, superior, inserted FPD technology. Most participants felt that this approach has worked fairly well in the past and could do so in the future. Nevertheless the participants felt some nervousness about taking this laissez faire approach concerning something so important to the nation's security.

The second possibility was that DoD could play a more useful role by being very active in FPD procurement. This role would include many activities, most of which are referred to in the paragraphs above. As stated above, they include: development of Department-wide, common procurement training; generation of an FPD technical road map; establishment of commonalty/standard products; and management of a flexible investment source to provide funds where needed. This second formula seemed to the majority of participants to be the only sensible approach to navigate through the development issue related to an emerging technology such as FPD.

These alternatives are likely to be mutually exclusive. That is, DoD must do one or the other; a combination is probably unstable.

RECOMMENDATIONS

Our participants strongly recommend that DoD establish a steering/oversight panel to accomplish the tasks listed above. This panel should be permanent (lasting at least ten years). Its members should be asked to serve for at least two years to provide continuity. Assignments need not be full time jobs; the panel would probably need to meet every three or four months. The members should be able to provide a balanced view of every issue. They should represent all of the Services, as well as several industry segments. They should also have balanced skill backgrounds (i.e., engineering, government, management, finance).

Above all, the panel should be empowered to implement its recommendations through the strength of member's job responsibilities or the panel's influence of top level OSD officials.

One important feature of the panel remains to be determined. Although DoD should probably sponsor and establish the panel, it is not clear that it should chair and manage it. Arguments could be made that the panel chair should come from the most prevalent segment of the industry, that of the system integrator. Certainly, DoD should be an active participant in the panel's proceedings, but it should take its rightful role as the dominate customer and not as the industry decision maker. It was felt that this aspect of the panel needs more consideration by it's likely members.

Appendix F: TEST AND EVALUATION STANDARDS AND PROCEDURES

FLAT PANEL DISPLAY STANDARDS

Standards are critical for performing uniform Test and Evaluation (T&E) procedures. The following list and description of relevant military and commercial standards is drawn from a compilation by Timothy W. Jackson, et al., of the Air Force Research Laboratory.[6] The authors note that there are a number of standards, but the Video Electronics Standards Association (VESA) is in the process of establishing a new standard that combines the best attributes of the existing ones. Unique military requirements, such as those related to the Night Vision Imaging System (NVIS), will still need to be addressed by military standards or handbooks.

AMLCD DRAFT STANDARD

As FPDs started to be developed for military cockpits and similar applications, the Air Force's Cockpit Avionics Office at Wright-Patterson AFB began to develop a functional specification for a "flat panel cockpit displays" (FPCD).[7] The need for a FPCD specification and a companion AMLCD standard was seen to be the "opportunity to establish common display modules for use in several platforms across services." In 1994, the Air Force Research Laboratory published a draft standard for AMLCDs.[8]

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6 Timothy W. Jackson, Reginald Daniels, Darrel G. Hopper, "Display Test Evaluation: Facilities, Standards, Procedures," in Darrel G. Hopper, Editor, *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Proceedings, SPIE 3057, pp. 514-525, 1997.

7 Hopper, (1994), p.2. "a-Si" stands for amorphous silicon.

8 Other FPD technologies, particularly electroluminescent and plasma, have been used in military applications, but their application to aviation cockpits is limited by technical issues concerning brightness for sunlight readability and other concerns. Field Emission Displays (FEDs) for use in avionics applications are still in the research.

The AMLCD standard includes requirements concerning standard sizes, luminance, contrast, luminance variation, gray levels, chromaticity, chromaticity tolerance and desaturation, response time, reflection, physical characteristics, maintainability requirements, and environmental conditions. The design baseline for flight instruments developed in this specification is an amorphous silicon (a-Si), thin film transistor (TFT) active matrix on glass substrate with chip-on-flex 16 gray level drivers and a backlight using fluorescent tubes coupled with 6850:1 dimming circuitry and a 10:1 contrast ratio. The standard states that the preferred pixel shape is square and a full color pixel comprises four subpixels (independently addressable elements). Desired pixel densities (pixels per centimeter) were stated for different application needs, such as monochrome for night vision, direct-view full color, helmet and head mounted, etc.

This baseline was developed recognizing that AMLCD technology, as well as other types of display technologies, were rapidly improving with many options appearing on the horizon. For example, while amorphous silicon “glass” is the dominant substrate today, displays using substrates of polycrystalline silicon (p-Si) and single crystal silicon (x-Si) are being developed to achieve faster transistors for greater display performance. In addition plastic substrates are being explored for both reduced cost and for the prospect of developing flexible displays.

MIL-HDBK-87213 ELECTRICALLY OPTICALLY/GENERATED AIRBORNE DISPLAYS

This handbook replaced AFGS-87213B “Display, Airborne, Electronically / Optically Generated.” It covers rationale, guidance, and lessons learned for the development of military avionic displays, as well as head-down, head-up, and helmet-mounted displays. Also included are requirements concerning luminance and contrast, chromaticity difference, luminance uniformity, and dimming range.

SAE ARP 4260

Photometric and colormetric measurement procedures for airborne FPDs are described by the Society of Automotive Engineers (SAE) in their Aerospace Recommended Practice (ARP) SAE ARP 4260. Although aimed at AMLCDs, the standard can be applied to other types of FPDs.

VESA FPD MEASUREMENT STANDARD

The goal of this effort is to define a group of basic measurement procedures for characterization of direct-view FPDs, including liquid crystal, electro-luminescent, plasma and field emissive. These procedures are intended to compliment other evolving FPD standards and the long-term goal is to expand the scope to include projection systems incorporating flat panel image sources, head-mounted displays, and head-up displays. This standard is currently in draft, but is expected to receive full VESA approval by Summer, 1998.

ISO 13406-2

The International Organization for Standards (ISO) is developing a standard called ISO 13406-2: Flat Panel Display Ergonomic Requirements. A number of display and display content characteristics are covered, including chromaticity uniformity difference, fill factor, display luminance, contrast, luminance balance, reflections, luminance uniformity, color differences, flicker, design viewing distance, character height, stroke width, character format, and default color set.

NVIS COMPATIBILITY: MIL-L-85762A AND ASC/ENFC 96-01

Night Vision Imaging System (NVIS) compatibility is increasingly a requirement for many military applications, however there is no commercial standard to cover NVIS testing. MIL-L-85762A was published in 1988 to serve as the standard definition and interface criteria for NVIS compatibility. Recently the Air Force developed Interface Document ASC/ENFC 96-01: Lighting, Aircraft, Interior, Night Vision Imaging System Compatible. Elements of this document are similar to the earlier document, but there are additions concerning various classes of exterior lighting, and procedures for doing sunlight readability testing. In its current form, ASC/ENFC 96-01 is to serve as an interim documents to be used as an interim replacement for MIL-L-85762A. It is expected to become a military handbook when finalized.

ENVIRONMENTAL TESTING: RTCA/DO-160C

The Radio Technical Commission for Aeronautics (RTCA) published RTCA/DO-160C "Environmental Conditions and Test Procedures For Airborne Equipment" to address environmental testing of avionics equipment. The standard covers testing for temperature and altitude, temperature variation, humidity, shock, vibration, explosive atmosphere, waterproofness, fluids, susceptibility, sand and dust, fungus resistance, salt spray, magnetic effect, voltage spike, icing, and tests for susceptibility to magnetic and electric fields as well as lightning.

FLAT PANEL TEST AND EVALUATION PROCEDURES

Three classes of test and evaluation (T&E) must be carried out during an FPD's product lifetime. They are: (1) laboratory; (2) production / quality assurance; and (3) maintenance / flight readiness tests. Laboratory testing occurs during product concept exploration and engineering and development phases. Tests are performed on prototype or low rate initial production (LRIP) units during or after the application of simulated environmental conditions. Production / quality assurance testing verifies that displays have been manufactured or repaired to meet specified requirements. Maintenance / flight readiness testing verifies that display performance remains within acceptable limits during operation and deployment. There are a number of procedures used for FPD T&E. The following subsections describe the main categories.[9]

PHOTOMETRIC, COLORMETRIC, AND RADIOMETRIC T&E PROCEDURES

Photometric, colormetric, and radiometric T&E procedures are used to ensure that required visual characteristics are met. Devices such as spectroradiometers, photometers, and colormeters are used to measure and analyze FPD radiant energy output. Many of the critical measurements for these procedures are outlined in SAE ARP-4260, Draft Standard for Color AMLCDs in U.S. Military Aircraft, MIL-HDBK-87213, and in the draft VESA FPD measurement standard.

ENVIRONMENTAL T&E PROCEDURES

Military displays must be able to withstand a wide range of environmental extremes in temperature, humidity, shock, salt spray, magnetic fields, etc. These extremes occur within operational and storage environments and require displays to be tested to

[9] Jackson, et al., p. 2.

ensure they can operate immediately and withstand all anticipated environments. MIL-STD-810E provides test methods and procedures for the wide range of environmental conditions. However, because DoD is using commercial products when possible, commercial standards such as the Radio Technical Commission for Aeronautics (RTCA) DO-160C are also used.

PHYSICAL, MECHANICAL, AND ELECTRICAL T&E PROCEDURES

Displays must meet volume, weight, power and interface requirements. T&E is particularly important with respect to form-fit-function (F3) upgrades or pre-planned product improvements (P3I) to existing CRTs or electromechanical instruments. RTCA DO-160C, MIL-STD-464 “Electromagnetic Environmental Effects Requirements for Systems”, MIL-STD-461 and MIL-STD-462 provide test methods and procedures for these requirements.

QUALITATIVE T&E PROCEDURES

Because human users look at FPDs in variety of situations, quantitative tests must be augmented human qualitative testing. Human factors engineering guides are used in this regard.

Appendix G: CLADS Performance Criteria

With respect to the CLADS program, Battelle has performed T&E on a variety of display technologies. These include AMLCD, AC Gas Plasma and Digital Mirror Device™ from Texas Instruments. Based on T&E to date, the following critical performance criteria have been meet or exceeded by one or more of the technologies tested by Battelle.

- Display colors: 24 bit
- Anti-reflectance: <4% specular reflectance
- Resolution: 1280(h) x 1024(v)
- Contrast: 10:1 at 20 fL luminance and 20 fc diffuse
- Contrast control: adjustable from 2:1 to greater than 10:1
- Luminance: adjustable from 0.1 fL to greater than 30fL (Sunlight readable optional)
- Reliability: > 3350 hours MTBF for an air inhabited cargo environment anticipated
- Self test: yes
- Temperature:
  - Operating: -20°C to 55°C
  - Non-operating & storage: -40°C to 70°C
- Altitude:
  - Operating: 0 to 10,000 feet, full performance
  - Operating: -2.5 hours up to 25,000 feet at 25°C
  - No damage for 5 minutes to 42,000 feet at 25°C
- Humidity
  - Operating: to 85% relative humidity
  - Non-operating: to 100% with condensation
- Temperature shock
  - Operational with sudden changes over -20°C to 55°C
- Explosive atmosphere
  - No ignition with gas mixture to 42,000 ft. per RTCA / DO-160C
- Vibration

  - Survive vibration requirements, RTCA / DO-160C, Section 8 with vibration envelope per spec: 2.0g rms & 3.7g rms
- Operational shock / crash safety: 6g / 30g
- Explosive decompression
  - No damage with pressure changes from 8,000 to 42,000 ft. in 5 sec. followed by a change from 42,000 to 25,000 ft. in no less than 5 minutes
- Dynamic acceleration
  - Withstand dynamic acceleration forces.
- Warm-up time
  - Full performance within 30 minutes for turn on below 0°C
- Transportability
  - Withstand shipping (in container) without damage
- EMI
  - Comply with MIL-STD-461 as modified in the spec

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LIST OF ACRONYMS

ABCCC	Airborne Battlefield Command and Control Capsule
ADC	Avionics Displays Corporation
AF	Air Force
AMLCD	Active Matrix Liquid Crystal Display
AR	Aspect Ratio
ARP	Aerospace Recommended Practice
ASC/ENFC	Aeronautical Systems Center/Engineering Directorate, Crew Systems Branch
a-Si TFT	Amorphous Silicon Thin-Film Transistors
ATM	Automated Teller Machine
AWACS	Airborne Warning and Control System
BAFO	Best and Final Offer
C4I	Command, Control, Communications, Computers & Intelligence
CAGR	Compound Annual Growth Rate
CDC	Computing Devices Canada
CLADS	Common Large Area Display Set
COG	Chip on Glass
COTS	Commercial-Off-The-Shelf
CRT	Cathode Ray Tube
DARPA	Defense Advanced Research Projects Agency
DMD	Digital Mirror Device
DoD	Department of Defense
DPA	Defense Production Act
DVE	Driver Vision Enhancement
ELD	Electroluminescent Display
EMD	Engineering Manufacturing Development
EMI	Electromagnetic Interference
F3	Form-Fit-Function
FED	Field Emission Display

FLIR	Forward Looking Infra-Red
FPCD	Flat Panel Cockpit Display
FPD	Flat Panel Display
GDLS	General Dynamics Land System
HMD	Head-Mounted Display
IDA	Institute for Defense Analyses
IO	Input/Output
IPT	Integrated Product Team
IR&D	Internal Research and Development
ISO	International Organization for Standards
ITO	Indium Tin Oxide
JEMC	Joint-Service Electronic Map/Chart
JSTARS	Joint Surveillance Target Attack Radar System
LC	Liquid Crystal
LCC	Life Cycle Cost
LCD	Liquid Crystal Display
LCU	Lightweight Computer Unit
LED	Light Emitting Diode
LRIP	Low Rate Initial Production
LRP	Low-Rate Production
LRU	Line Replacement Unit
MBTF	Mean Time Between Failure
MLRS	Multiple-Launch Rocket System
NFPDI	National Flat Panel Display Initiative
NRE	Non-Recurring Expenses
NVIS	Night Vision Imaging System
O&S	Operations and Support
OIS	Optical Imaging Systems
OSD	Office of the Secretary of Defense
PCB	Prorated Circuit Board
PDA	Personal Data Assistant

PDP	Plasma Display Panel
PWB	Printed Wiring Board
R&D	Reesearch and Development
RGB	Red, Green, Blue
RGBG	Red, Green, Blue, Green
RMS	Root Mean Squared
RTCA	Radio Technical Commission for Aeronautics
S&T	Science and Technology
SAE	Society of Automotive Engineers
TAB	Tape Automated Bonding
T&E	Test and Evaluation
TFT	Thin-Film Transistor
TPU	Turret Processing Unit
UDLP	United Defense Limited Partnership
USD(A&T)	Under Secretary of Defense for Acquisition and Technology
UV	Ultra Violet
VESA	Video Electronics Standards Association
VFD	Vacuum Fluorescent Display
VFP	Vacuum Fluorescent Panel
XVGA	Extend Video Graphics Array